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Design of the National Bureau of Standards Isotropic Magnetic Field Meter (MFM-10) 300 kHz to 100 MHz

J.E. Cruz
L.D. Driver
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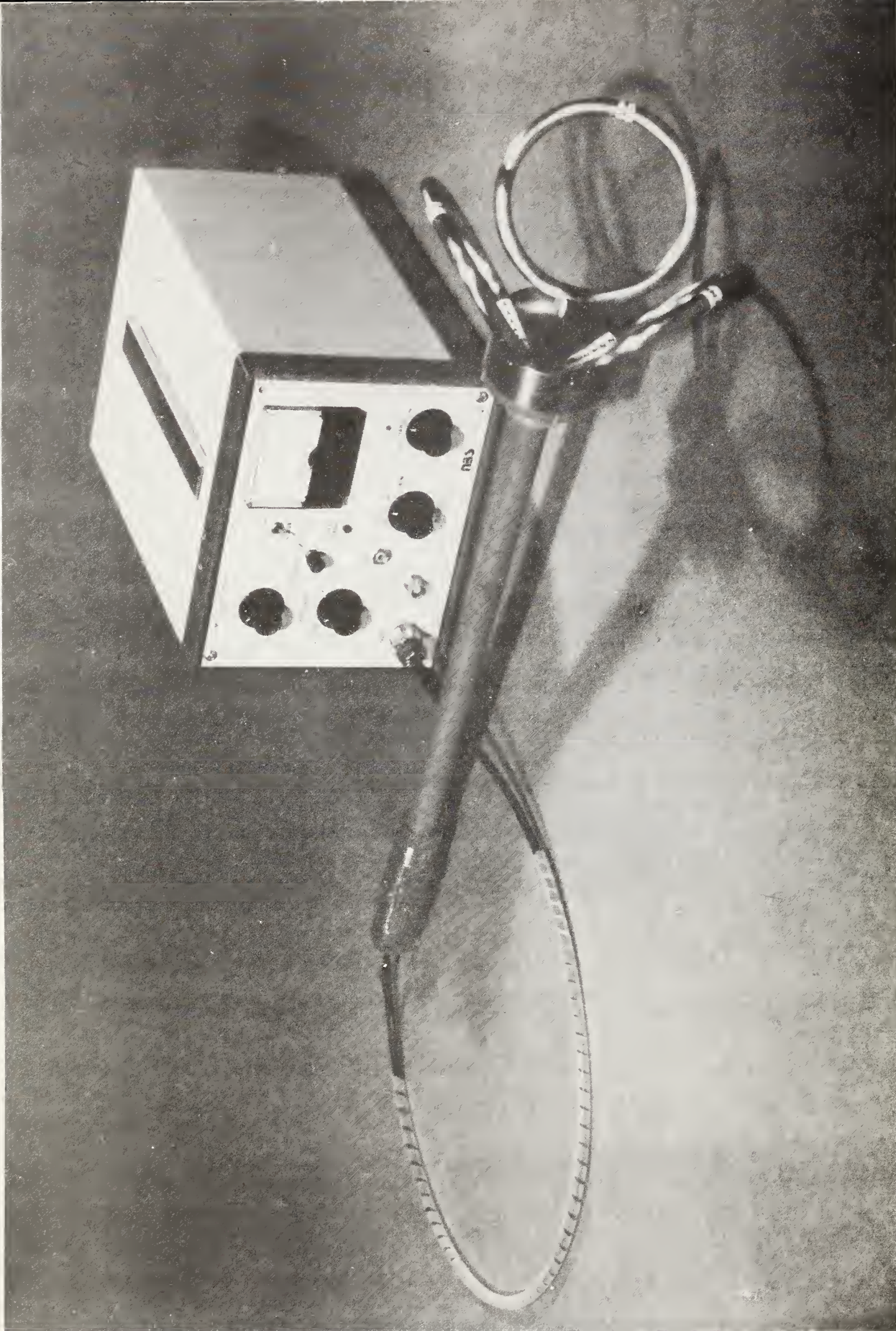
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Frontspiece. Photograph of the MFM-10 rf radiation monitor

**Design of the National Bureau of Standards
Isotropic Magnetic Field Meter (MFM-10)
300 kHz to 100 MHz**

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A broadband magnetic field meter has been developed at the National Bureau of Standards (NBS) for the frequency range of 300 kHz to 100 MHz. The isotropic antenna unit consists of three mutually orthogonal loops, each 10 cm in diameter. The magnetic field probe described in this paper has a measurement range of 0.1 to 30 A/m. The readout of the meter is in terms of the Hermitian or "total" magnitude of the magnetic field strength which is equal to the root-sum-square value of the three orthogonal magnetic field components at the measurement point. This magnetic field meter is nearly isotropic over its dynamic range.

The electronic circuitry of the meter obtains the total magnitude of all field polarizations for all cw signals in the entire frequency band. The sensor is isotropic and is well suited for measuring the near field of an emitter, including regions of multiple reflections and standing waves. The meter can be used to monitor either the plane wave fields in the far zone of a transmitter, or the complicated fields very close to an rf leakage source. This report describes the design, performance and operating instructions for the MFM-10.

Key words: electromagnetic field; electronic instrument design; field strength measurements; isotropic antenna; probe design.

1. Introduction

The rapid increase in the electromagnetic (EM) contamination of the environment has produced a growing concern regarding electromagnetic interference (EMI) and electromagnetic compatibility (EMC). Numerous proposals have been generated for electromagnetic radiation standards and for more rigorous means of characterizing the electromagnetic environment. This concern has spawned the development of small portable hazard meters. Most of these meters have been designed to measure the electric component of the electromagnetic fields. The measurement of the electric component is quite adequate for plane (far-field) waves; it does not describe the fields in the near zone where the relationship between the electric and magnetic components is ambiguous. Only

recently have instruments become available which measure the magnetic component of the electromagnetic environment. Unfortunately, these instruments have been found to exhibit one or more of the following limitations: (1) limited frequency coverage, (2) restricted dynamic range, (3) insufficient protection against burnout, (4) susceptibility to electromagnetic interference (EMI), (5) inability to measure field polarization, and (6) the need for multiple probe heads for full range coverage.

The MFM-10 is a new instrument developed by NBS to provide near-zone magnetic field measurements in the frequency range of 300 kHz to 100 MHz. This meter offers significant improvements over the various shortcomings mentioned above. The MFM-10 magnetic field meter consists basically of three components. These are: (1) an rf probe assembly, (2) a high resistance transmission line, and (3) a signal processing metering unit.

The rf probe assembly is composed of three orthogonally mounted loops. The voltages induced into these loops are detected, filtered, and transmitted via the lossy transmission line to the metering unit. The three detected voltages are amplified, corrected for square law response, scaled, and displayed either separately or as the root-sum-square (rss) magnitude of all three voltages.

The MFM-10 magnetic field meter provides a number of improvements over the presently available instruments of its type. These improvements include: (1) a frequency range of 300 kHz to 100 MHz, (2) a dynamic range of 44 dB, (3) a frequency response flat to within ± 1.0 dB, (4) isotropic response of ± 0.3 dB, (5) a 200% overload capability, and (6) the ability to measure and display each of the three orthogonal magnetic field components, as well as their rss magnitude. All of these features are realized using only one probe head.

The portable design makes the MFM-10 suitable for searching out areas of high field intensity which often exist in the near-zone regions. The ability to separately measure each of the three orthogonal H-field components makes the instrument suitable for making field polarization measurements of transmitting antennas and other strong radiating sources. The MFM-10 can also be

used for field mapping various types of radiating antennas and for doing exposure surveys near high-powered industrial sources. A photograph of the instrument is shown in the frontispiece.

In this report the following will be discussed: (1) design consideration of the broadband magnetic field sensor, (2) overall design of the magnetic field meter, (3) performance of the meter, (4) calibration and operating procedures, (5) alignment and adjustment procedures, and (6) summary and conclusions.

2. Design Considerations of the Broadband Magnetic Field Sensor

The basic evolution of the final design for the sensor starts with discussion of the short circuit current loop, continues with the discussion of the open-circuit voltage loop, and ends with the compensated open-circuit voltage loop and the effect of electrostatic shielding. This discussion is given to provide some physical insight into the operation of the shielded loop. The design consideration enabled the NBS researchers to select and design an appropriate loop configuration in order to meet the requirements of sensitivity and usable frequency range.

2.1 Short-Circuit Current Loop

The configuration of a short circuit current loop and its equivalent circuit are shown in figure 1. The transfer function $S(f)$ of a short-circuit current loop is found to be [1],

$$S(f) = \frac{V_L}{H_{inc}} = \frac{\mu\omega_0 NA}{\frac{1}{Q} + j(\delta - \frac{1}{\delta})} \quad (1)$$

The symbols have the following meaning:

V_L is the rf output terminal voltage

H_{inc} is the incident magnetic field strength

μ is the permeability of the loop core

N is the number of loop turns

A is the area of a loop.

$$Q = \frac{R}{X_0} = \frac{\omega_0}{\omega_h} = \frac{\omega_l}{\omega_0}$$

$$X_0 = \omega_0 L = \frac{1}{\omega_0 C}$$

$$\delta = \frac{\omega}{\omega_0}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} = \sqrt{\omega_h \omega_l} = \text{self-resonance angular frequency,}$$

where ω is the angular frequency of operation, L is the loop inductance, C is the loop capacitance plus any added external capacitance, ω_h and ω_l are respectively the high and low frequency ends of the 3-dB roll-off points. The normalized transfer function, i.e., $S(f)$ divided by $\omega_0 \mu N S$, is shown in figure 2.

For example, a 5-turn short-circuit current loop with a 10 cm diameter is chosen for a loop antenna over the frequency range of 100 kHz to 100 MHz. The self-resonance frequency is the geometrical mean of the low and high ends of the 3-dB roll-off points, i.e., $f_0 = 3.16$ MHz. The required Q of the loop antenna should be $Q = 0.0316$. Using eq (1), the transfer function of the antenna is calculated to be

$$S(f) = \frac{V_L}{H_{inc}} = 3.09 \times 10^{-2} \Omega m, \text{ or } -30.2 \text{ dB relative to } 1 \Omega m.$$

Since the inductance of the 5-turn loop antenna with a 10 cm diameter is about 6 microhenries [2], the required loading resistance is about 3.8 ohms.

It becomes apparent from this example that, although the short-circuit current loop configuration gives a very flat transfer function across a wide frequency range, it exhibits relatively poor sensitivity. For this reason, the configuration of an open-circuit voltage loop is considered.

2.2 Open-Circuit Voltage Loop

The configuration of an open-circuit voltage loop is shown in figure 3. Using Maxwell's equation with Stoke's theorem, the induced voltage, V_i , is determined by [3]

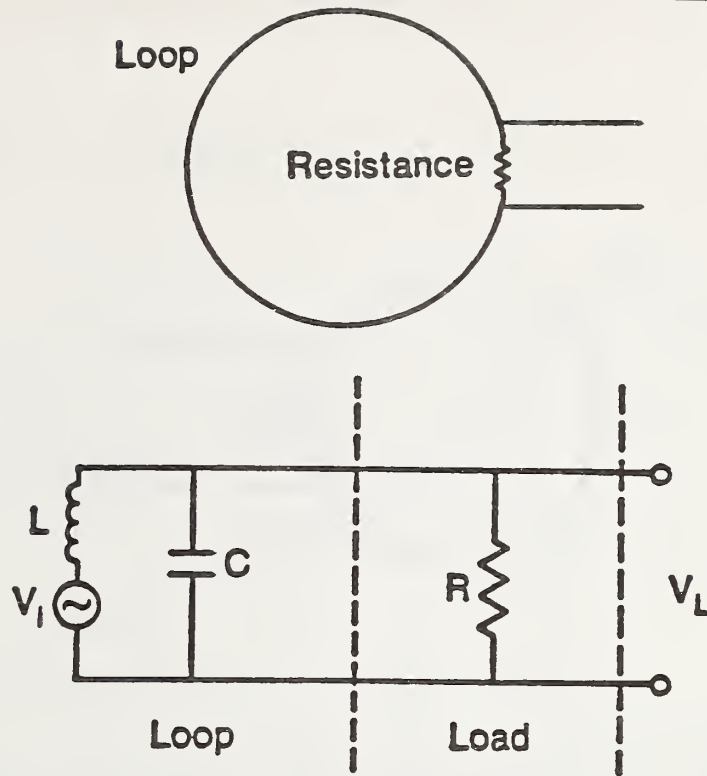


Figure 1. Short-circuit current loop and its equivalent circuit

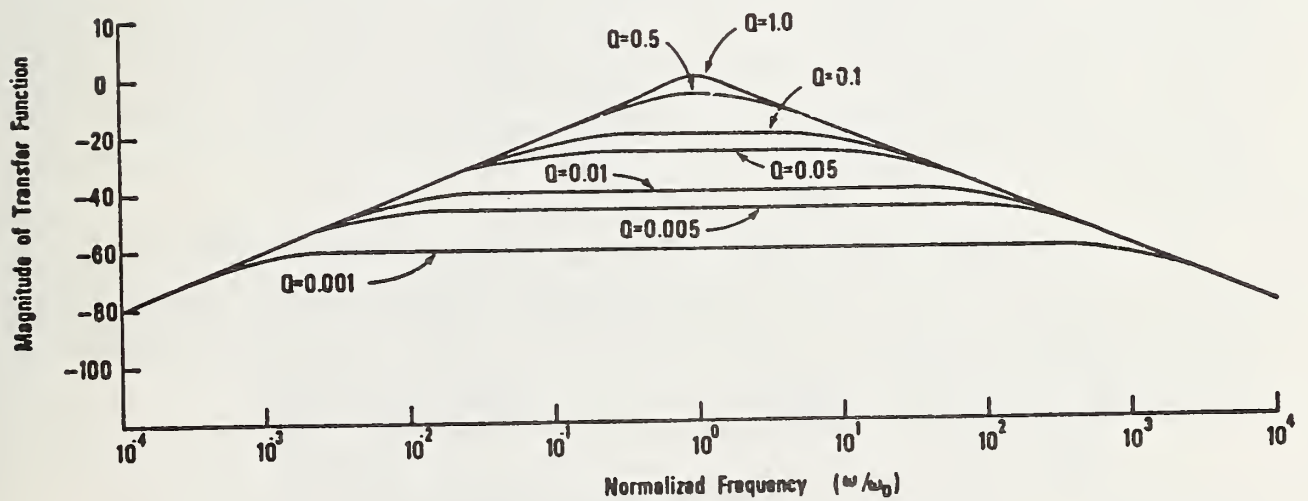


Figure 2. Normalized transfer function for short-circuit current loop

$$V_i = -j \omega \mu H_{inc} NA. \quad (2)$$

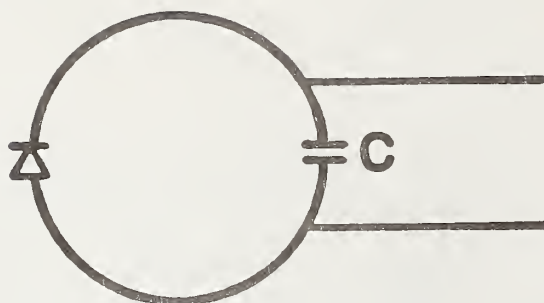


Figure 3. Open-circuit voltage loop

As can be seen, the response of the loop is proportional to frequency, loop turns, and the area of the loop.

As an example, the response of the single turn loop with a 10-cm diameter is shown in figure 4. The response of the loop is clearly proportional to frequency. The loop exhibits a resonance at about 90 MHz, due to the inductance ($0.5 \mu\text{H}$) of a single-turn loop [2] and the loop and diode detector parallel capacitance (6 pF). The resonance of the loop at 90 MHz is well understood. There are higher resonances due to the loop inductance $L_a = 0.5 \mu\text{H}$ and the loop capacitance $C_a = 0.2 \text{ pF}$, the first of which is expected to be 477 MHz. The higher resonance frequencies can also be estimated from the fact that the total length of the loop is approximately equal to $\lambda/2$ or one of its multiples.

One of the major disadvantages of an open-circuit voltage loop is that the response of the loop is proportional to the frequency, which complicates its calibration and use. A "flat" transfer function is achieved by means of a compensated open-circuit voltage loop with a loading resistance.

2.3 Compensated Open-Circuit Voltage Loop

The configuration of a compensated open-circuit voltage loop and its equivalent circuit are shown in figure 5. In this configuration a series RC

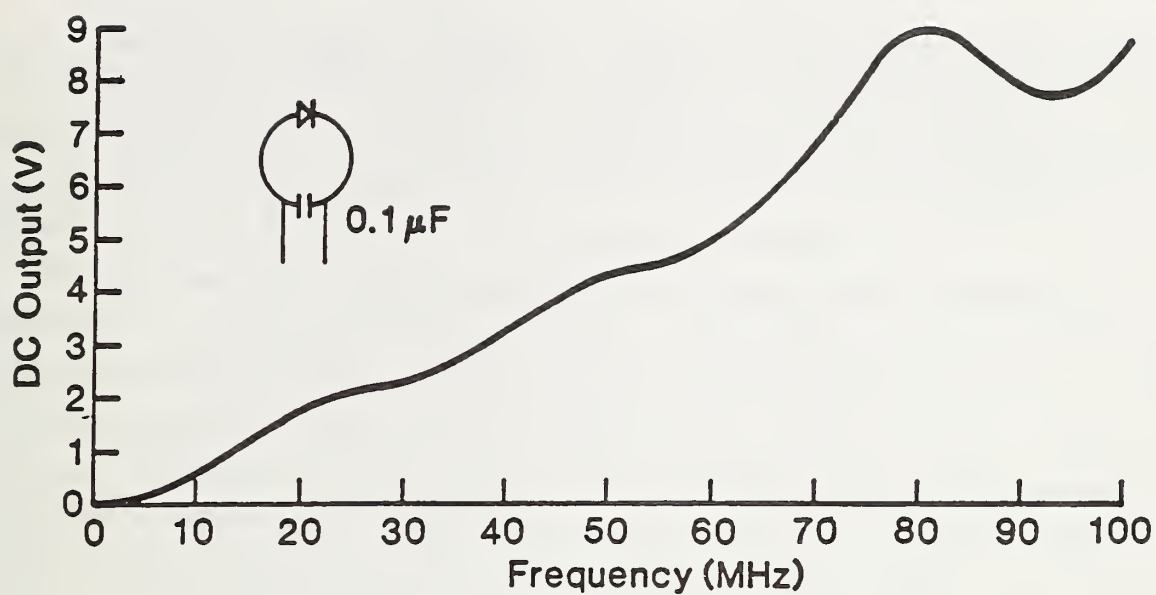


Figure 4. Response of open-circuit voltage loop (single turn, 10 cm loop)

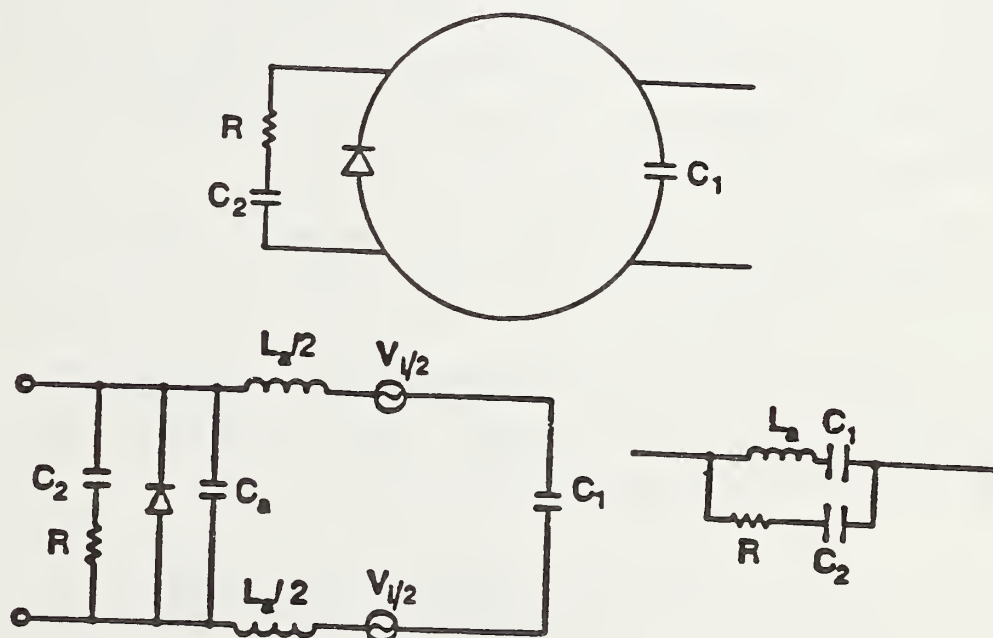


Figure 5. a) Compensated open-circuit voltage loop
b) and c) its equivalent circuit

circuit is added across the diode detector in order to lower the Q of the loop and shift its resonance to a lower frequency.

To gain some physical insight into a compensated open-circuit loop, consider a 5-turn loop with a 10-cm diameter in which a resistance R is added across a diode detector as shown in figure 6. Without this shunt resistance R, the sharp resonance of the loop is observed at about 23 MHz. Since the inductance of a 5-turn loop with a 10 cm diameter is about 7 μ H and the loop and a diode detector have a parallel capacitance of 6 pF, the loop resonance of about 23 MHz is very predictable. There are higher resonances, the lowest of which at 102 MHz is due to the loop inductance and the loop capacitance or equivalency. These resonances occur when the total length of the multi-turn loop becomes approximately equal to $\lambda/2$ or to one of its multiples. Thus, in this configuration, two distinct resonances are observed. To achieve a flat loop response, a shunt resistance R is added across the diode detector. Figure 6 indicates this phenomenon as a 330 ohm resistance is added across the diode detector. As expected, the resonance frequencies are not shifted through this compensation.

To further improve the flatness of the loop response, the shunt resistance R needs to be further reduced. At the same time, to shift the lowest resonance to around 100 kHz, the external capacitance C_2 in series with the resistance R is added across a diode detector as illustrated in figure 5. The capacitance also serves as a dc block.

For the purposes of determining the resonance frequencies of the compensated open-circuit voltage loop, its equivalent circuit given in figure 5b can be simplified as shown in figure 5c. Because the loop capacitance and the diode capacitance are much smaller than external capacitances C_1 and C_2 of 0.1 microfarads each, they can be ignored. Then the resonance frequency and the Q of the simplified equivalent circuit are given by [4]

$$f_0 = \frac{1}{2\pi \sqrt{L_a (C_1 // C_2) - (C_1 // C_2)^2 R^2}} \quad (3)$$

and

$$Q = \frac{2\pi f_0 L_a}{R} \quad (4)$$

where $C_1//C_2$ is the total capacitance of the two capacitances C_1 and C_2 in a series configuration.

As an example, the response of a 5-turn compensated open circuit voltage loop with a 10-cm diameter is shown in figure 7. Since the inductance of a 5-turn loop with a 10-cm diameter is about 7 μH , the resonance frequency is calculated from eq (3) and is found to be 600 kHz, which agrees well with experimental results.

The Q of the compensated open-circuit voltage loop is estimated to be 2.5 using eq (4). The resonance which occurs at about 106 MHz is the first of a series of high frequency resonances. These resonances are found to occur when the total length of the multi-turn loop is approximately equal to $\lambda/2$ or one of its multiples. In essence to achieve a broadband response using a compensated open-circuit voltage loop, the first resonance is shifted by adding proper capacitances of C_1 and C_2 , and its Q is adjusted by the series resistance R . Using both the lowest and next lowest resonances and adjusting the Q of the first resonance, one can achieve a broadband response of the loop antenna.

2.4 Effects of Electro-Static Shielding

The above physical discussion presupposes that the loop itself, as well as an attached line, and the load are symmetrical with respect to a plane perpendicular to the plane of the loop and passing midway between its symmetrically located terminals. Furthermore, if the loop antenna is near a conducting surface such as the earth, this surface must be parallel to the plane of the loop.

It is possible to achieve complete structural symmetry for a receiving loop by enclosing it entirely in a metal shield that has a gap at the top, or in some instances at the bottom. A potential difference is maintained across the gap, almost wholly as a result of current induced in the shield. In general, codirectional up and down current due to the electric field is also excited, but it contributes nothing to the potential difference across the gap because it charges the gap edges equally with charges of the same sign. Under

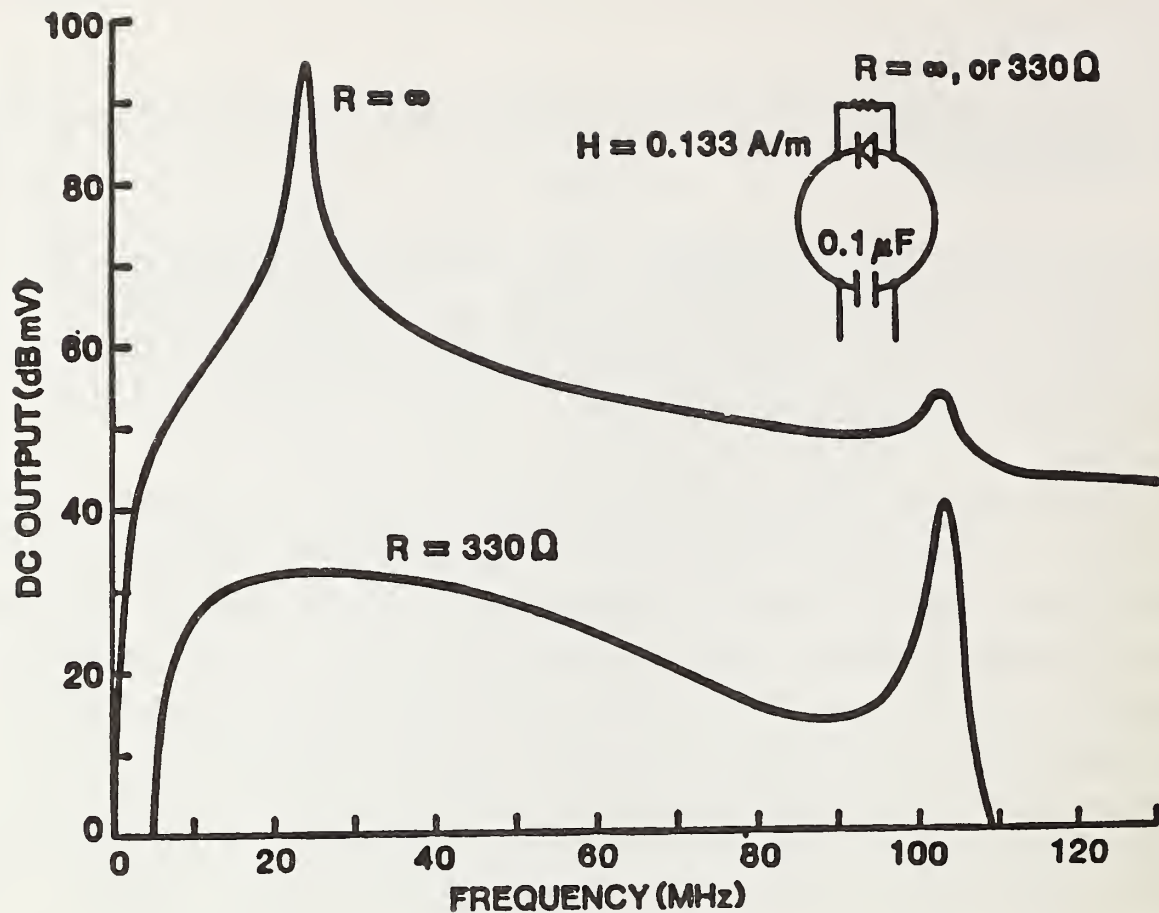


Figure 6. Response of compensated open-circuit voltage loop (5-turn, 10 cm loop)

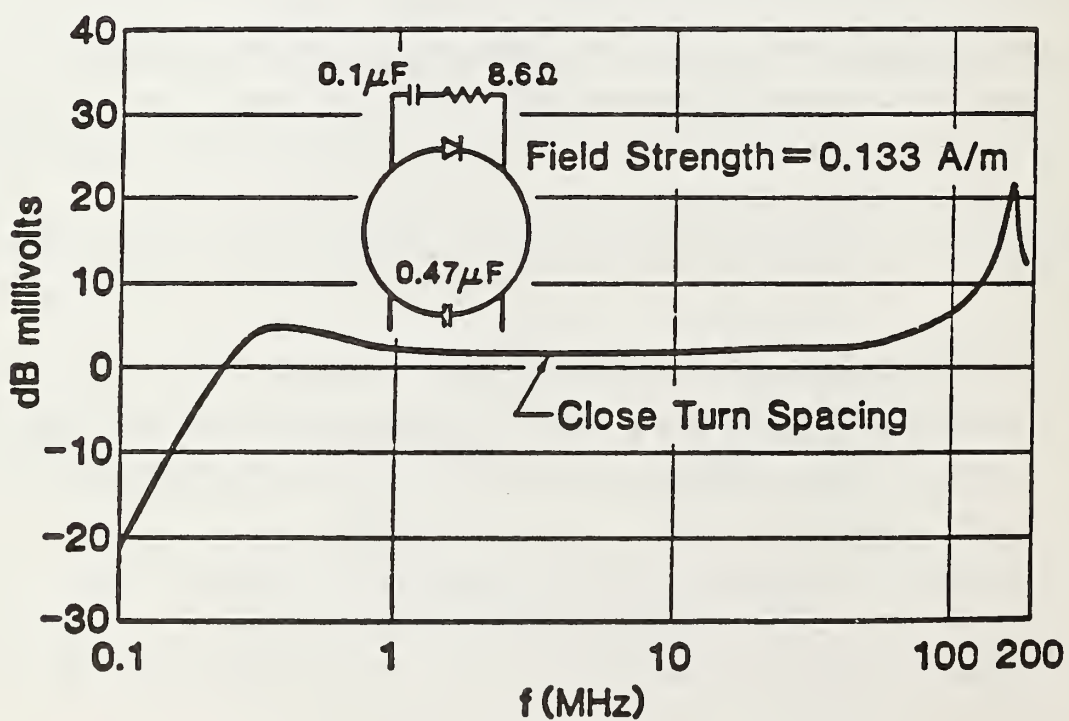


Figure 7. Response of compensated open-circuit voltage loop (5-turn, 10 cm loop)

these conditions, loop current is excited by the induced voltage across the gap, and this is due only to the circulating current in the shield.

In general, shielding has very little effect on the low frequency loop response. As the frequency increases, it has a very pronounced effect on the loop's high frequency response. The gap voltage, which is the product of the circular current and the gap impedance, decreases linearly with frequency, because the gap capacitive reactance decreases linearly with frequency. Thus the current in the loop, excited by the gap induced voltage, decreases linearly with frequency. Figure 8 shows the result of this high frequency filtering action in reducing some of the undesirable high frequency resonance.

3. MFM-10 Performance

3.1 Frequency Response

The MFM-10 magnetic field meter is designed to operate over a frequency range of 300 kHz to 100 MHz with a maximum variation of ± 3 dB. The frequency response of the MFM-10 is dictated solely by the rf probe, as it is the only frequency dependent component of the meter. Figure 8 shows the raw detected output voltage from the X channel loop of the rf probe assembly as a function of frequency from 300 kHz through 100 MHz. Similar response characteristics were determined for the "y" and "z" channel loops, and the maximum variation between the three curves was found to be less than ± 0.5 dB. It is important to note that the voltages comprising figure 8 were measured at the probe's output connector and have not yet been properly corrected and scaled to represent magnetic field strength. Consequently, once the voltages are properly processed the variations shown in this curve will be reduced by half. This is illustrated by the normalized response curve given in figure 9. The data comprising this curve were taken relative to the metering unit's output. This curve shows that the maximum variations of the MFM-10's frequency response are less than ± 1 dB.

3.2 Isotropic Response

The mutually-orthogonal configuration of the three magnetic-field sensing loops of the rf probe assembly results in nearly perfect isotropic response. This is illustrated by the response patterns shown in figures 10, 11, and 12.

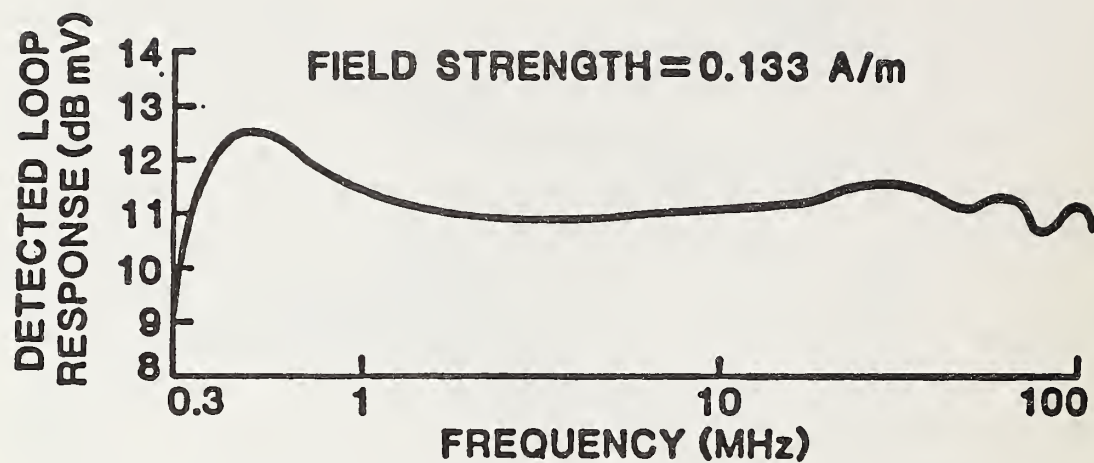


Figure 8. Response of compensated open-circuit voltage loop with shielding (5-turn, 10 cm loop)

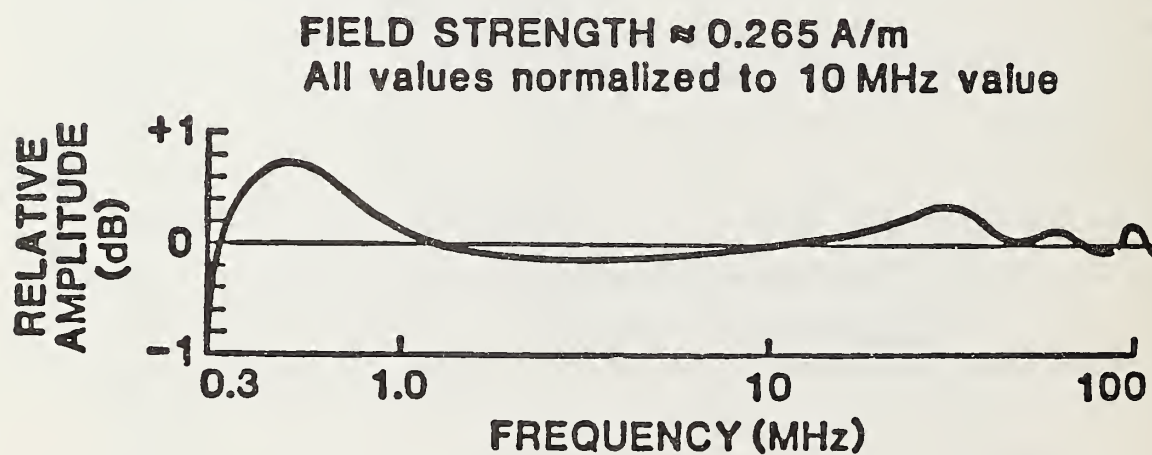


Figure 9. Normalized response of the MFM-10 vs frequency

The largest deviation from ideal isotropy shown in these patterns is ± 0.3 dB, which is well within the ± 1.0 dB design limit. The response pattern showing the largest variation is the one that was taken at 100 MHz. This is as expected since the largest variation between the responses of the three probe loops also occurs at 100 MHz. Also, the presence of an undesirable response appears on the 100 MHz response curves. These undesirable responses which are approximately 15 dB below the primary H-field response are suspected to be E-field responses. Some degree of E-field response is quite common with magnetic-field loop antennas [5].

3.3 Response Time

The response time of the MFM-10 is approximately three seconds. Most of this is caused by the response of the plastic high resistance transmission lines of the rf probe assembly. Several large values of capacitance were used in the design of the rf probe to get a flat frequency response. This three second response (for 95% of the final value) appears to be suitable for the measurement of cw fields. However, this response would be unsuitable for most measurements involving either modulated cw signals or pulsed rf signals.

3.4 Dynamic Range

The dynamic range of the MFM-10 is conservatively specified as 0.1 to 16 (A/m). Figure 13 shows curves of detected output of a typical MFM-10 loop as a function of field strength for several frequencies. Although these curves indicate operation to 50 A/m, it was found that simulated operation above 35 A/m caused overheating of the diode shunting resistor, R_1 of figure 15. Such overheating causes R_1 to permanently change in value, which alters the frequency response of the loop. Prolonged overheating causes R_1 to fail completely. Consequently the MFM-10 loop should never be exposed to field strengths greater than 35 A/m for more than just momentary periods.

4. Overall Design

Figure 14 is a functional block diagram of the major components of the MFM-10. The rf probe assembly consists of the loop antenna system, the diode

FREQUENCY = 300 kHz
FIELD STRENGTH = .265 A/m

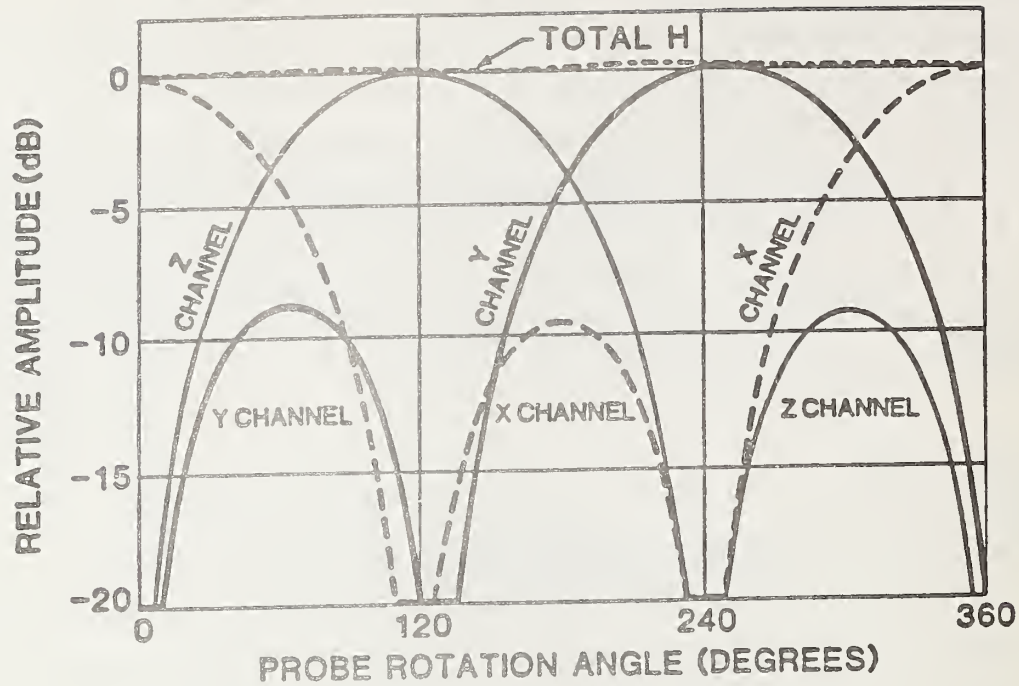


Figure 10. Response pattern of the MFM-10 probe at 300 kHz

FREQUENCY = 10 MHz
FIELD STRENGTH = .265 A/m

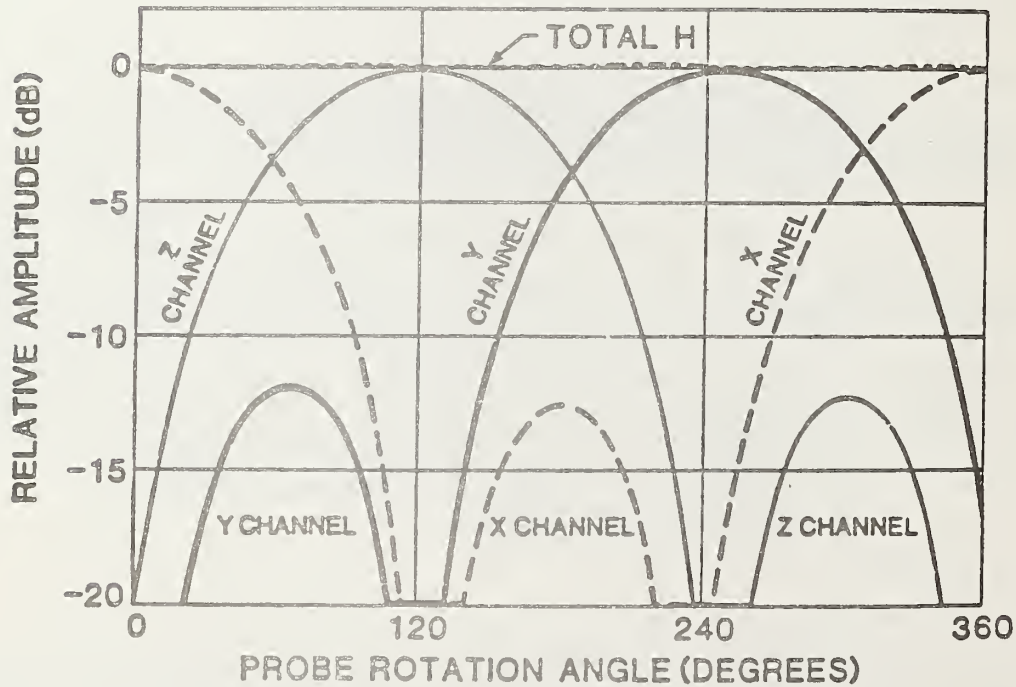


Figure 11. Response pattern of the MFM-10 probe at 10 MHz

FREQUENCY = 100 MHz
FIELD STRENGTH = .265 A/m

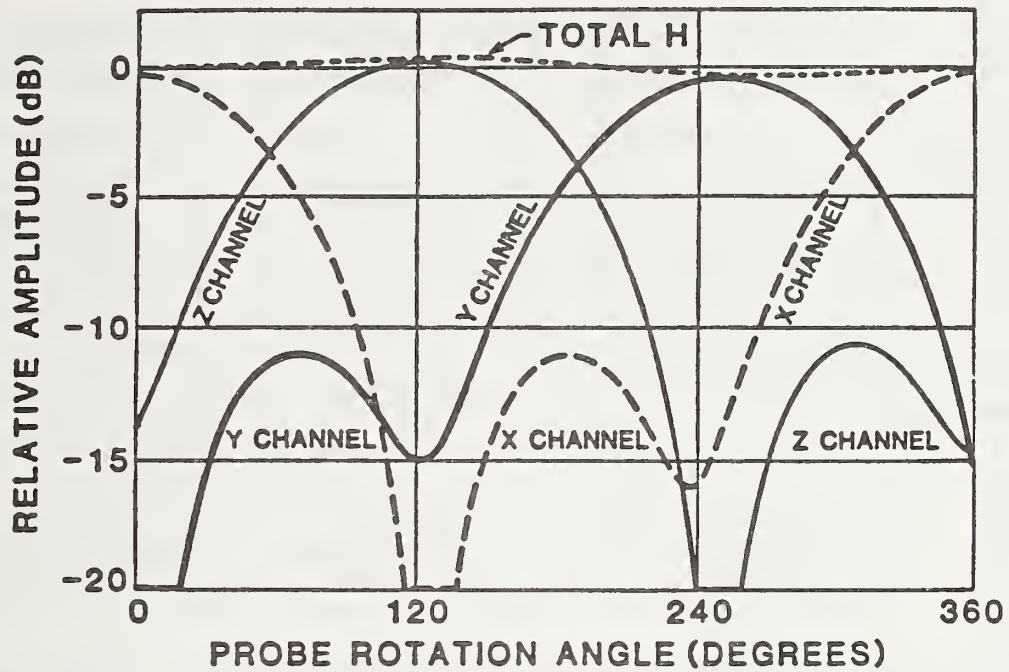


Figure 12. Response pattern of the MFM-10 probe at 100 MHz

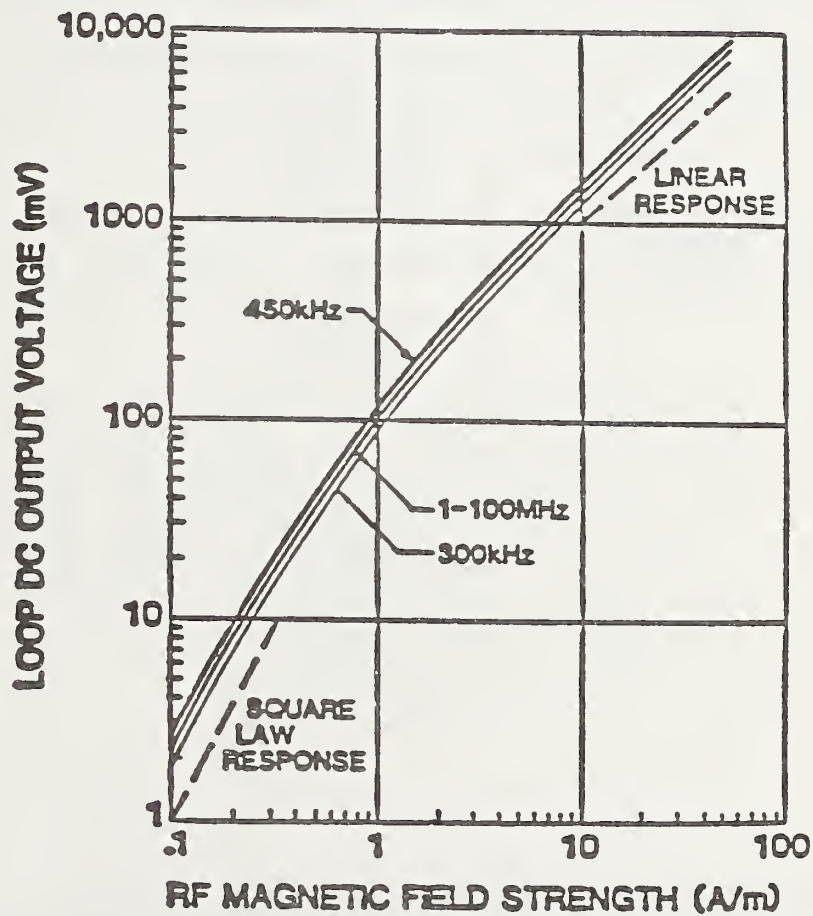


Figure 13. Typical detected output of the MFM-10 loop as a function of field strength, at several frequencies

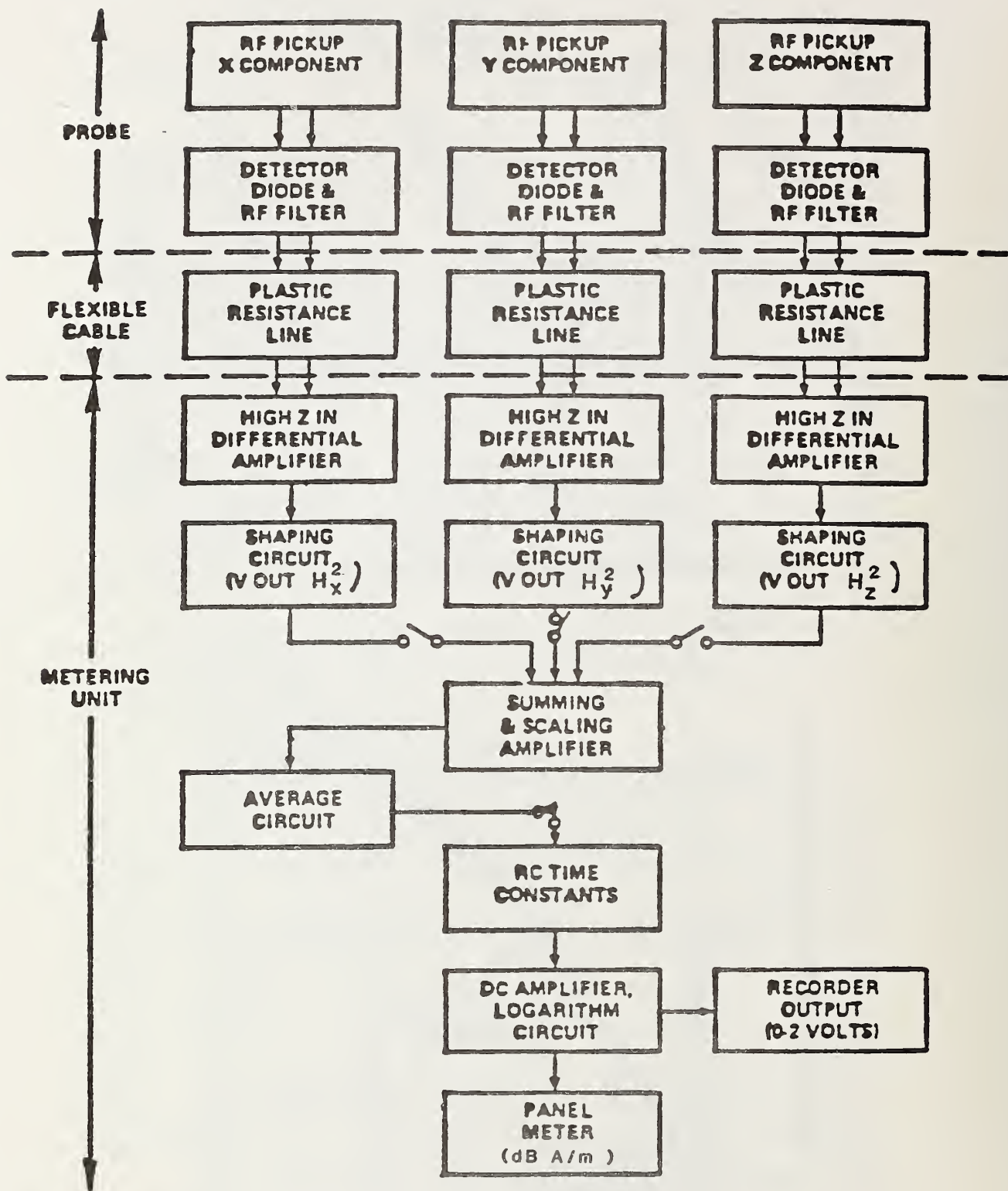


Figure 14. Functional block diagram of the MFM-10

detectors, and the high resistance transmission line. This resistive transmission line conveys the detected signals to the metering unit. This line is essentially invisible to EM fields, causing no appreciable distortion of the field being measured. The third and largest component, the metering unit, is inside a metal case. It consists of three balanced dc amplifiers and other circuitry which processes the voltages to produce the desired H-field readout.

The isotropic probe consists of the x, y, and z component loops with the associated detectors, filters, and transmission lines. It can be seen by examining figure 15 that the metering unit provides four major functions:

- (1) Amplification, including differential pre-amplifiers of high input impedance.
- (2) Processing of the detected signals to produce a voltage proportional to the square of the magnetic field over the entire amplitude range.
- (3) Switching to choose a single field component to combine the three voltages from the three coordinate channels to obtain a single "total magnitude."
- (4) Analog circuitry to calculate and produce a meter indication in units of dB with respect to 1 A/m.

The front panel range switch has three amplitude positions which are labeled -20 dB, 0 dB, and +20 dB. These correspond to the dB value which must be added to the dial indication in dB A/m. The channel selector switch on the front panel has four positions, labeled X, Y, Z, and TOTAL. These positions correspond to the measurement of either a single H-field component or the root-sum-square magnitude of all three orthogonal components.

5. Component Description

5.1 The rf Probe Assembly

The rf probe assembly consists of: (1) three mutually orthogonal loop antennas mounted on a top plate, (2) a probe base housing, (3) a 4.57 cm

hollow glass epoxy probe handle, and (4) a 1 meter section of 6 conductor resistive transmission line. The mechanical and electrical configurations of a single loop antenna of this assembly is depicted in figure 15.

The internal portion of the loop is composed of a length of No. 26 AWG enameled wire, having a detector network located at its center, a bypass capacitor connected between its two ends, and formed in such a fashion as to produce a 5-turn loop antenna. The axial lead semiconductor diode, D_1 , provides rectification of the signal induced in the loop antenna. The bypass capacitor, C_3 , partially smooths this rectified signal. The diode shunting elements, R_1 and C_1 , are necessary to produce the flat frequency response of the antenna. The values of these components, R_1 and C_1 , as well as that of C_3 influences both where and how rapidly the response rolls off at the low frequency end.

A balanced R-C filter, consisting of C_4 , C_5 , R_3 , R_4 , R_5 , and R_6 is connected across C_3 . This filter network is included to (1) provide additional filtering to the rectified voltage appearing across C_3 , and (2) to prevent any rf voltage picked up by the conductors of the resistive transmission line from being rectified by D_1 . The values of C_4 and C_5 are not critical, but the values of R_3 , R_4 , R_5 , and R_6 are critical in presenting equal resistive paths to the resistive transmission line. Connected to the output of this filter network is the three-foot section of resistive transmission line.

A hollow metal cylinder, shaped in the form of a loop, houses the internal 5-turn loop assembly. This outer loop has a 1.5 mm gap and a small opening on its bottom where it mounts to the top plate. The filter network is located in the metal probe base housing attached to the underside of the top plate. The entire outer assembly, consisting of the antenna loops, the top plate, and the probe base housing, constitutes a continuous equipotential surface. The only openings in this surface are the top gaps of the three outer loops and the probe handle opening located on the underside of the probe base housing. This equipotential surface significantly reduces errors resulting from common-mode E-field response of the rf probe assembly.

The Schottky-barrier detector diode has a reverse breakdown voltage rating of 70 volts, thus making it virtually burnout proof in this

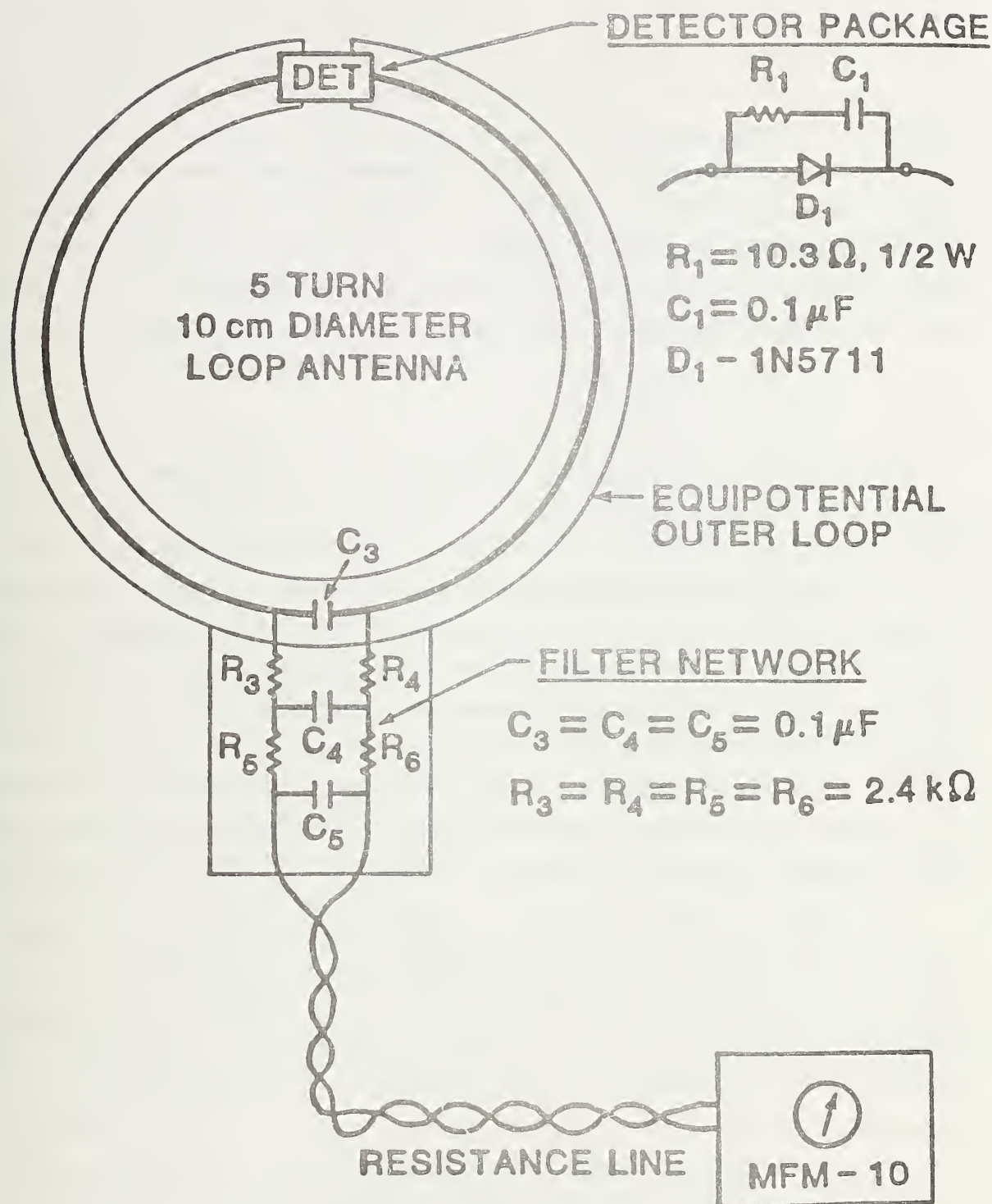


Figure 15. Schematic diagram of an individual loop antenna of the rf probe assembly

application. The element that is of primary concern during overload conditions is the shunting resistor, R_1 . Since this resistor constitutes an rf load in the loop, it must be able to accommodate the total voltage induced in the loop. For the maximum overload condition, the power that R_1 must dissipate is approximately 1.5 watts. To accommodate this overload capability, a 1/2 watt carbon resistor is used for R_1 . This resistor is firmly attached to the inside surface of the metal outer loop with a highly conductive metal base epoxy. These heat-sinking measures used to protect R_1 are sufficient to increase its dissipation capacity by several times its rated value.

5.2 The Resistive Transmission Line

Transmission of the detected responses of the loop antennas of the rf probe assembly to the signal processing unit can involve significant errors unless special precautions are taken to isolate electronically the transmission device from the ambient electromagnetic field. For example, the use of metallic transmission lines often results in large measurement errors because they can: (1) perturb and disturb the field being measured, and (2) interact with the field to produce unwanted induced currents [5]. Such difficulties are essentially eliminated through the use of a completely non-metallic electrical transmission line. This line is "transparent" to the field in the sense that it causes negligible scattering or perturbation to the field, and negligible induced current flow on its high resistance conductors.

The 1 meter resistive transmission line consists of six non-metallic conductors. Each conductor has been fabricated from Polytetrafluorethylene (PTFE) plastic which has been rendered slightly conductive by carbon loading [5]. The loading is such as to produce a dc resistance of approximately 656 ohms per cm. Each conductor is nylon jacketed to provide electrical insulation and mechanical strength. The six conductors of the transmission line are placed inside a slightly conductive heat-shrinkable sheath. This carbon-loaded polyolefin sheath reduces the "electrometer effect" which is caused by dc fields and by low frequency fields.

5.3 The Signal Processing Metering Unit

5.3.1 Direct Current (dc) Buffer Amplifiers

The detected output from each of the three loop antennas is filtered by a balanced R-C network inside the probe assembly. The three filtered voltages are conveyed through flexible resistance lines to the metering unit. Figure 16 is a sketch of the controls and the front panel layout, showing the INPUT terminal for the resistance line. The instrument case is portable and normally held by the operator. Each of the three dc signals is applied to the input of an integrated-circuit preamplifier in the metering unit.

As shown in figure 17, each preamplifier is configured from three operational amplifiers to form an extremely high impedance differential amplifier. The high input impedance minimizes the voltage drops on the conductors of the resistive transmission line. The actual loading of each loop antenna is 20 Mohms, set by the two resistors at the input of each preamplifier. The balanced input of each preamplifier minimizes common-mode pickup on the transmission line and prevents it from being detected by the diode in the loop antenna. Great care is exercised in the construction and circuitry of the MFM-10 to achieve a high common-mode rejection ratio. The differential mode pickup of each 10 cm loop is large compared with any signal resulting from common-mode voltage on the line. Because the instrument has individual channel selector switches, it is easy to compare the unwanted common-mode response with the desired loop response. This test is done by placing the antenna in a strong EM field and aligning the probe so that one loop is perpendicular to the magnetic field, while the other two loops are parallel to the magnetic field. Any response or meter indication from the two loops which are oriented parallel to the magnetic field is an indication of poor common mode rejection ratio.

The gain control potentiometers in the feedback circuit of the mid-amplifier buffers are used to get equal sensitivity in the three channels. During calibration of the instrument, using a standard field, each loop is aligned perpendicular to the magnetic field and the appropriate potentiometer is adjusted to get the correct indication. This adjustment compensates for slight differences in loop geometry, diode sensitivity, and capacitance. The three-position channel selector switch permits disconnecting two antennas at a

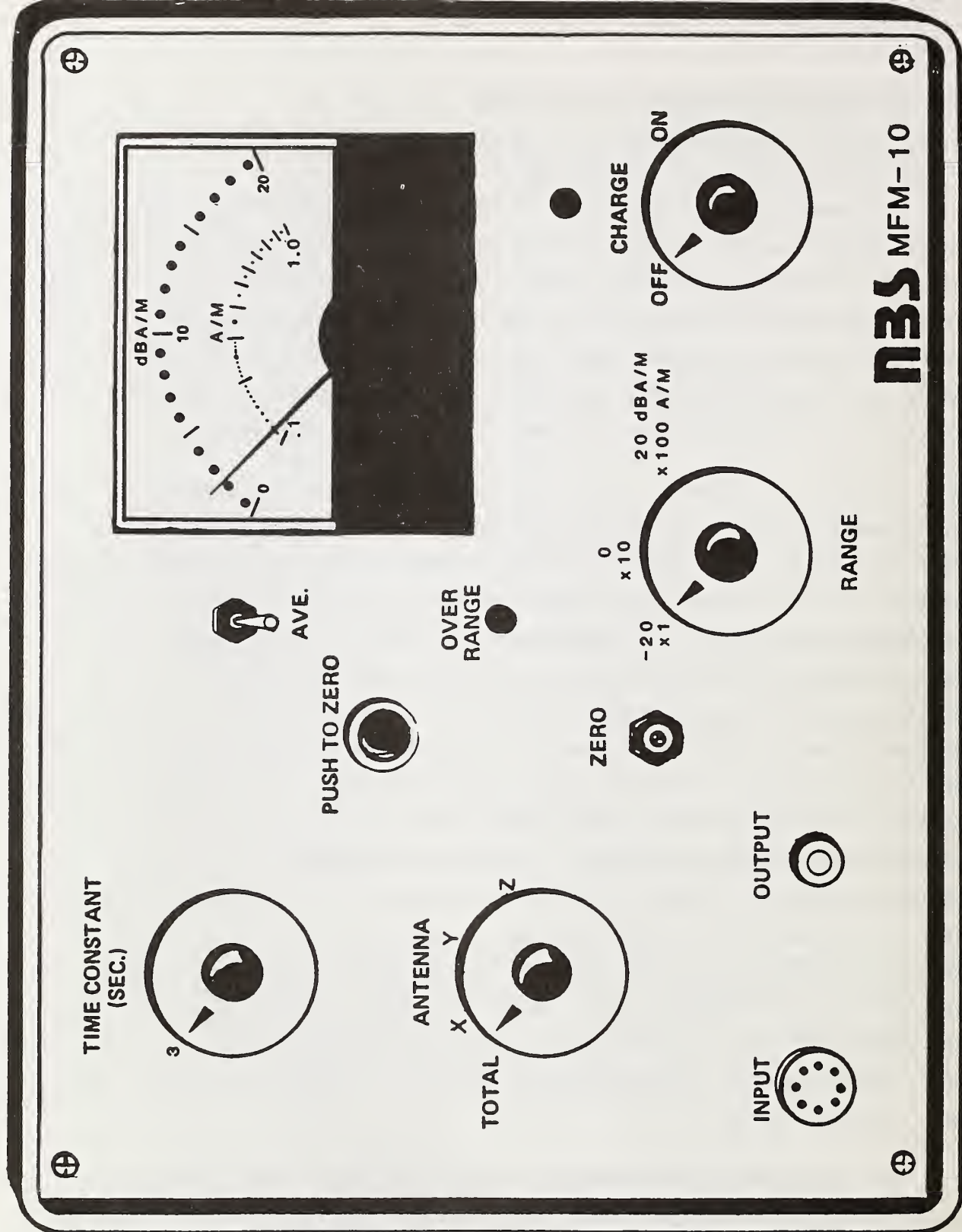


Figure 16. Front panel layout of the MFM-10 metering unit

time when making this adjustment. The overall gain of the MFM-10 is adjusted for correct indication of each channel at a field level of 1 dB A/m and at a frequency of 10 MHz. Most of the circuitry required for this gain adjustment, as well as that needed to get electrical zeroing of all the operational amplifiers, has been omitted from figure 17 for the purposes of simplicity. The X, Y, Z, and TOTAL rotary switch is useful for several purposes. In addition to channel selection, it is used when setting the gain control and checking the common-mode rejection. The channel selector switch is also useful during trouble shooting and checking the general operation of the rf probe assembly.

5.3.2 Nonlinear Adder and Scaling Circuitry

The output signal of each of the three mid-amplifier buffers, in figure 17, is applied to a summing amplifier. The operational amplifier used for the adder has a field-effect-transistor input stage. The overall purpose of the circuit is to produce a signal voltage which is proportional to the sum of the squares of the three separate magnetic field components incident on the three orthogonal loops. Before adding the signals from the three channels (X, Y, and Z), it is necessary to process or "shape" each detected voltage to make its amplitude proportional to the square of the magnetic field component. This is accomplished by using a special non-linear resistor (varistor) at the input circuit of each added channel as shown in figure 17.

Because many non-linear circuit elements are temperature sensitive, some care is necessary when selecting an optimum type of varistor. The shaping circuits chosen for the MFM-10 meter use silicon carbide material with a temperature coefficient that is nearly an order of magnitude less than that of silicon, and silicon is better than germanium by about an order of magnitude.

The adder has a two-decade voltage output for each single decade of field strength, or to put it differently, the output voltage of the adder varies as the square of the field level. As shown in figure 17, the adder output voltage extends from about 0.01 to 1 volt for each position of the three-position range switch.

5.4 Logarithm and Metering Circuitry

The outputs of the average circuit are voltages that increase from about 0.01 to 1 volt over each of the three available one-decade ranges in field strength. The output in each range is proportional to the square of the measured magnetic field value. The next stage of the MFM-10 is an operational amplifier buffer with a gain of ten, producing a voltage which varies from 0.1 to 10 volts for each decade range in field strength. This voltage is also proportional to the square of the magnetic field. Following this gain is the logarithm circuitry required to produce a voltage proportional to dB A/m at the OUTPUT jack. This circuitry is shown as a single block in the simplified schematic of figure 17.

The complete logarithm circuit consists of an integrated-circuit logarithmic amplifier, two operational amplifiers, and two potentiometers. One potentiometer (LOG ZERO) sets a regulated voltage to get zero volts output for a 0.1 volt input. Any rf field which produces an output of less than 0.1 volt will cause a negative deflection on the output meter. The logarithmic amplifier produces an output which varies in direction proportion to the logarithm of the input voltage. Another potentiometer (LOG SLOPE) sets the gain of the logarithm module to get 2 volts output for 10 volts input. The voltage at the OUTPUT jack of figure 17 varies linearly (in dB A/m) across each range in direct proportion to the magnetic field.

5.5 Power Supply, Operating Controls and Special Features

Power to operate the MFM-10 meter is furnished by a series string of 32 rechargeable nickel cadmium cells. The individual cells are size AA, which have a nominal 1.3 volts and a 450 mA hour capacity. The battery voltage is about ± 15 volts for the MFM-10 circuitry and +5 volts for the field-effect-transistor switches. The battery drain is about 80 mA from the positive side and about 70 mA from the negative side. The battery life is about seven hours for continuous operation of the field strength meter, and the time required for recharging the batteries is about 10 hours. To recharge the batteries after use, a power cord is connected to the back panel of the metering unit, plugged into a 115 V ac outlet, and the three-position power switch on the front panel is turned to the CHARGE position.

The field strength meter does not operate with the three-position power switch turned to the CHARGE position. The battery charging circuit is not operative with the power switch in an ON position, even if a power cord is plugged into a 115 volt outlet. A light emitting diode (LED) located above the power switch glows whenever the batteries are being charged. The same LED glows if the instrument is turned ON and the battery voltage is low, indicating that the batteries should be recharged. It is possible that the batteries may be so completely discharged that the voltage is insufficient to light the LED.

The battery charging circuit consists of a commercially available power supply and two constant-current sources, each supplying 40 mA of current. Diodes are used at the charger output terminals to prevent the batteries from discharging back into the charger when the power switch is on CHARGE. Diodes also prevent the LED from glowing unless the batteries are actually being recharged.

Several self-checking features have been built into the MFM-10 circuitry, such as the LED located above the power switch. Another LED labeled OVERRANGE can be seen in the center of the front panel. This warning light indicates that the output meter is pegged full scale, on any of the three ranges.

Three removable "cards" in the metering unit contain most of the electronic circuitry. These may be mounted on extender boards for calibration, adjustment, and trouble shooting. The power supply, charger, and batteries are mounted directly on the main chassis. Connections between the front panel and back plane are made with ribbon cables.

6. Operating Instructions for the MFM-10

The input connector in the lower left corner on the front panel of figure 16 is for the six-conductor resistive line from the probe unit. The OUTPUT connector furnishes the 0 - 2 V signal which is proportional to the 0 - 20 dB scale of the readout dial. The three-position switch in the lower right corner is the power ON/OFF switch, plus a battery charging position. The instrument is inoperative when this switch is rotated to the CHARGE position. A

115 V power cord must be plugged in the rear of the meter to recharge the batteries. For normal operation during field strength measurement, the power cord should be disconnected from the instrument in order to reduce field perturbation.

The step-by-step procedure for operating the MFM-10 as a field intensity meter can be summarized as follows:

- (1) Connect the plastic transmission line from the probe to the INPUT connector of the metering unit, located in the lower left corner of the front panel.
- (2) If desired, a coax cable (or other dc line) may be used to connect an X-Y recorder (or other voltage monitor) to the BNC OUTPUT jack, adjacent to the INPUT connector.
- (3) Turn the power switch (lower right corner of the front panel) to the ON position. A red light-emitting diode (LED) located near this switch will light up if the battery voltage is low, indicating that the batteries should be recharged. (Note: If the batteries are nearly completely discharged, there may not be enough voltage to light the LED.) This warning light also glows when the switch is in the CHARGE position and a power cord is plugged into a 115 V outlet, to indicate that the batteries are being charged.
- (4) Rotate the ANTENNA channel selector switch to the TOTAL position. This switch is located on the left side of the panel. The TOTAL position is used for measuring the RSS value of the three orthogonal magnetic field components.
- (5) Place the PEAK/AVG toggle switch to the AVG position for measuring the time-average value of the field strength.
- (6) Rotate the TIME CONSTANT switch to the 3 sec. position.
- (7) Before zeroing the instrument, rotate the RANGE selector switch to the most sensitive (-20 dB) position. Check the meter zero by

depressing the PUSH TO ZERO button. If necessary, turn the zeroing potentiometer with a small screwdriver until the indication is at 0 dB or 0.1 A/m on the meter dial. This ZERO adjustment is accessible on the front panel below the PUSH TO ZERO switch.

- (8) To measure field intensity, place the probe at the desired measurement location, and read the meter. If A^2/m^2 are desired, simply square this result.
- (9) To measure a single X, Y, or Z field component, follow the above procedure and rotate the channel selector switch to the desired component position. If the meter has been zeroed for all-channel operation, it should be re-zeroed for single-channel operation, and vice versa; this is especially true for measurement of a very weak field on the most sensitive range.

When the front-panel PUSH TO ZERO switch is held in, the logarithm circuit is disengaged and the ZERO control should then be adjusted for a 0 dB dial indication. It is necessary to place the probe in a shielded or zero-field environment during the zeroing process.

Measurements of ambient fields are generally made by using the instrument to find the higher H-field values present at any location within reach of the hand-held probe. During the field measurement process, the sensor end of the probe is moved side-to-side by the operator over a vertical plane region about 2 x 2 meters. The ambient field measurements reported then represent the highest levels found during the scanning process.

6.1 Calibration and Performance Tests of the MFM-10

6.1.1 Description of NBS Standard-Field Calibrations

The MFM-10 meter is normally calibrated with respect to the following parameters: (1) dial indication versus field level, (2) response versus frequency, and (3) probe isotropy, that is, antenna directivity and field polarization sensitivity. The calibration provides data for corrections which may

be applied to the dial indication to obtain more accurate measurements of field strength.

It is assumed here that the original alignment and adjustments of the MFM-10 instrument have been completed. The initial "shaping" or linearizing procedure is described in section 6.1.5. In general the "shaping" or linearizing is required only once, as part of the instrument manufacturing process. A calibration as described in this section is done more routinely, perhaps once a year for each radiation monitor. Such a "routine" calibration determines the extent to which the monitor does not indicate the true or correct value at a given field intensity and MFM-10 range, at a given frequency, for a given field polarization.

Theoretically, it would be possible to calibrate rf radiation monitors in far-zone, plane-wave fields at all frequencies and levels; however, the transmitter power required to produce intense fields would generally exceed 1 kW. An alternative approach is used at NBS in which lower-power rf sources of 20 to 200 W are adequate. It involves calculation of the field intensity within a transmission line or in the near zone of a transmitting antenna. The probe to be calibrated is inserted in this field of known magnitude. The optimum instrumentation for generating a standard (calculable) field depends on the frequency, intensity, and required accuracy. One technique being used at NBS is described briefly in this report for calibrating the MFM-10.

6.1.2 TEM Cells, 100 kHz to 150 MHz

At frequencies up to about 150 MHz, a transverse electromagnetic (TEM) cell is a convenient device for calibrating a radiation monitor. This type of calibrating chamber consists of a large "coaxial" 50 Ω transmission line in which the center conductor is a flat metal strip and the outer (grounded) conductor has a rectangular cross section [8,9,10,11,12]. At frequencies sufficiently low so that only the principal wave (TEM mode) is propagating through the cell, it produces a fairly uniform EM field which can be calculated easily and quite accurately. Both the E- and H-field magnitudes are given in terms of the plate spacing and measured voltage or throughput power. The standard field is then used to calibrate a radiation monitor directly, or to calibrate a small loop probe for use as a transfer standard.

A block diagram of the instrumentation used to produce a standard field in a TEM cell is given in figure 18. The electric field strength at the calibrating point shown (midway between the center conductor and bottom of the cell, and midway between the input and output connectors) is given by the equation

$$H = \frac{V}{377 D} = \frac{\sqrt{50 P}}{377 D} \quad (8)$$

where

H = magnetic field strength, A/m,

V = voltage between the center conductor and outer walls of the TEM cell, V,

D = distance between the center conductor and bottom of the cell, m,

P = power conveyed through the cell, W, and

50 = characteristic impedance of the transmission cell and resistance of the cell termination, ohms.

The TEM cell used at NBS to cover the 100 kHz to 150 MHz frequency range has a 0.6 m x 1 m cross section and a length of 2 meters. The value for D in eq (8) is thus 0.3 meters. This cell is accurate for frequencies up to about 150 MHz, but above this frequency higher-order waveguide modes may cause errors. This is similar to the unwanted resonances which occur at higher frequencies in shielded rooms.

6.1.3 Calibration of the MFM-10 Response as a Function of Frequency and Field Intensity

The calibration of a radiation meter consists of comparing the field intensity indicated on the dial with the correct value, at each desired signal frequency and field level. To accomplish this, the probe is immersed in the standard field (of known level) of the calibrating chamber. A 0.6 x 1 m TEM cell is generally used for frequencies up to 150 MHz.

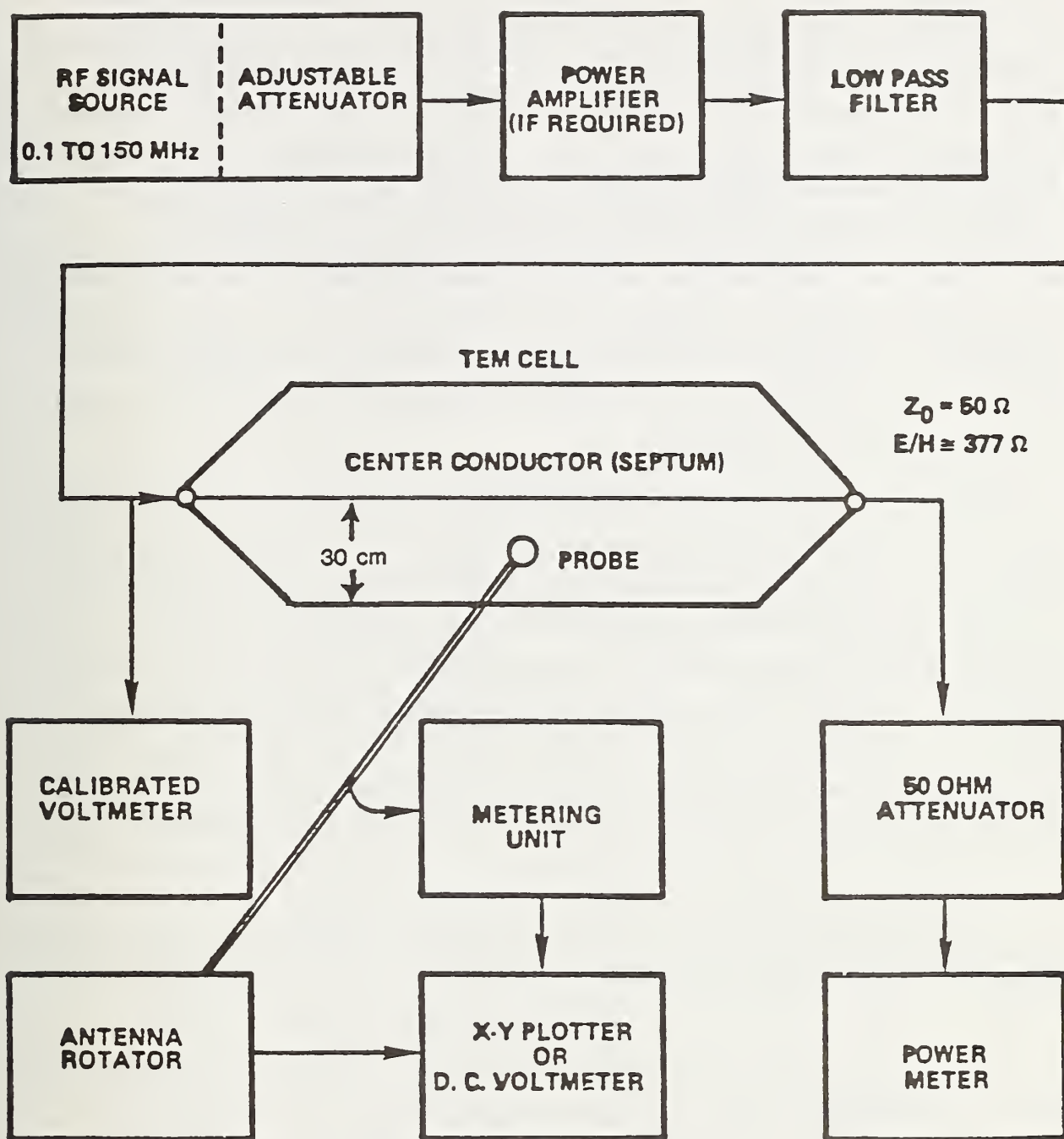


Figure 18. Instrumentation for generating a standard field in a TEM cell for calibrating an MFM-10 meter

During a calibration the MFM-10 probe is mounted with dielectric supports on an antenna rotator/positioner. The probe is located at the point indicated in figure 19 in the TEM cell. The MFM-10 probe is mounted in the TEM cell with the probe handle aligned at the "analytical angle." The analytical angle is defined as the angle which the diagonal of a cube makes with the three intersecting edges at one corner of the cube. It is also the angle at which the probe handle makes equal angles with the E-field vector, H-field vector, and Poynting vector. For each calibration point (given frequency and intensity) the probe is held at the analytical angle and rotated 360° on an axis through the probe handle. An X-Y recording is made of the probe response versus rotation angle. A separate plot is made for each individual channel of the probe (X, Y, and Z) and a fourth plot is made with the ANTENNA selector switch in the TOTAL position. The latter recording corresponds to the usual isotropic response of the probe.

One critical test of probe isotropy (non-directivity) is to record, separately, the response of each of the three loops as a function of field orientation. For this test, the probe handle is set at the analytical angle and the probe is rotated axially in the test field. At 120° intervals in the rotation, one loop of the probe will be perpendicular to the H vector (maximum response). The curves, figure 11, show the separate loop responses, each of which should ideally peak at the standard field value but should equal zero when the loop is oriented parallel to the H-field. The curves also show the RSS output for total H (upper line) for normal operation of the MFM-10 meter.

The following procedure is used to obtain the response curves in figure 11. It is recommended that this type of "checkout" calibration be made at 10 MHz preceding each probe calibration.

- (1) Turn the MFM-10 power switch ON at least 15 minutes before starting the calibration.
- (2) Note: It is recommended that all the operational amplifiers within the electronic package of the MFM-10 be zeroed; otherwise, it is possible that the total zero offset of the instrument will exceed the range of adjustment of the front panel control.

- (3) Set up the instrumentation of figure 19 to obtain a standard field at 10 MHz in the 0.6 x 1 m TEM cell.
- (4) Mount the probe in the TEM cell with the handle fixed at the analytical angle.
- (5) With no power into the TEM cell, rotate the ANTENNA selector switch to X-channel position, depress the PUSH TO ZERO switch, and adjust the ZERO control for 0 dB indication of the meter.
- (6) Adjust the intensity of the standard field to the desired calibrating level.
- (7) Rotate the probe axially (manually) until the angle of maximum response corresponds with 0° on the X-Y recorder.
- (8) Record the pattern response of the X channel only, from 0° to 360° axial rotation angle. The response should peak at the standard field value at 0° rotation angle. The indication should drop to more than 20 dB below 0.1 A/M at angles of 120° and 240°.
- (9) Repeat the response recordings for the Y channel alone and the Z channel alone, zeroing the meter with the front panel control before each recording.
- (10) Rotate the ANTENNA switch to the TOTAL position to obtain the vector magnitude of all three channels. Re-zero the meter and record the normal isotropic pattern response.

This completes the initial calibration check point. The remainder of the calibration points are obtained in a similar manner.

An estimate of the overall calibration uncertainty is given as follows:

- (1) The largest source of error in the MFM-10 calibration is uncertainty of the standard field value in the TEM cell. This uncertainty in

the TEM cell is due to field enhancement caused by the probe. The estimated maximum error is ± 0.5 dB.

- (2) Another source of calibration error is uncertainty in the perturbation of the field in the TEM cell by probe leads. This error is estimated to be less than ± 0.2 dB.
- (3) Other sources of calibration uncertainty are associated with TEM cell plate spacing and NBS calibration of the various instruments used. The overall error due to these latter sources is estimated to be less than ± 0.3 dB.
- (4) A possible source of calibration error is drift from "zero" indication of the meter, especially if the ambient temperature is changing or if the meter has not been turned on for a sufficient length of time.

The overall worst-case uncertainty of the calibration is the simple sum of those listed above, or ± 1 dB.

Note: A possible source of error is the electric dipole response of a loop antenna. This phenomenon is discussed by Greene [5] and could introduce an error as high as 1.6 dB in the measurement of magnetic fields.

6.1.4 Probe Isotropy

Isotropic response patterns have been recorded for the MFM-10 probe for several of the above configurations, over the frequency range of 300 kHz to 100 MHz. The pattern obtained with the probe handle fixed at the analytic angle is the most critical test of probe isotropy. If an rf monitor has switches for reading the three field sensors individually, the test can be used to analyze the overall probe quality. This is the origin of the term "analytic angle." The pattern obtained in figure 11 is the easiest method to demonstrate experimentally whether a probe is truly isotropic. From past experience in evaluating the response versus orientation angle of rf radiation monitors, it is known that an isotropic response will be achieved if: (a) the three loops have separate "maximum" responses which are equal in amplitude but

displaced 120° from each other on the X-Y recording, and (b) the three "minimum" responses in the recording have zero amplitude, or are at least 30 dB below the maximum value. Note that the three loops in each MFM-10 prototype antenna have been adjusted for equal response at a frequency of 10 MHz and a field level of 1 A/m. It is assumed here that accurate signal processing has been achieved in obtaining the Hermitian magnitude of the three orthogonal signal components.

6.1.5 Alignment and Adjustment Procedure

This section describes the procedure for making the (initial) adjustments of the internal potentiometers in the MFM-10 metering unit. A "shaping" operation is performed in order to produce the correct meter indication as a function of field intensity. This non-linear processing is required for field strength levels above 1 A/m. The frequency chosen at NBS to perform the signal shaping is 10 MHz. The standard field setup is accurate and convenient at this frequency and the MFM-10 response curve is essentially flat. The shaping procedure involves an iterative adjustment of the nonlinear adder circuitry, for each channel, to achieve an optimum overall readout accuracy. That is, potentiometers are set to achieve minimum error in indicated field strength over the total measurement range of 0.1 to 16 A/m.

The first stage in the shaping procedure is to "zero" all the op-amps in the metering unit. The probe antenna must be in a zero-field (shielded) environment for this step, for example inside a TEM cell. The basic alignment procedure involves adjustment of the receiving gain controls and shaping controls until the meter indicates the correct field strength value, for each of the three loops in the isotropic antenna. The shaping adjustments are made with the MFM-10 probe inserted in the standard magnetic field of a TEM cell, using the instrumentation shown in figure 18.

There are three removable electronic circuit boards in the metering unit. They have been designated in this report as: (a) preamplifier board, (b) shaping board, and (c) logarithm board. Figures 19, 21, and 23 are photographs of these three main boards showing the internal alignment potentiometers and voltage test points. The following procedure is used to make the amplitude/shaping adjustments within the metering unit, producing a meter

indication which is proportional to the RSS value of the measured H field as expressed in dB above or below 1 A/m.

- (a) Mechanical zero. With the OFF/CHARGE/ON power switch in the OFF position, check the mechanical zero of the meter movement. If required, adjust the screw located on the meter housing to obtain a 0 dB indication.
- (b) Battery check. With the power switch in the ON position and no 115 V cord plugged into the back panel, check the battery voltage. If the warning LED located above the power switch does not glow, it indicates that the battery voltage is sufficient for proper operation of the MFM-10 meter. Do not leave the power switch in the ON position when the instrument is not in use because the battery life is only about seven hours. (NOTE: If the batteries are discharged, they may be too weak to light the LED.)
- (c) Preliminary setting of the front panel switches and controls.
 - (1) Power switch in the OFF position.
 - (2) Field intensity RANGE selector switch in the -20 dB A/m step, corresponding to the maximum sensitivity range of -20 to 0 dB A/m.
 - (3) PEAK/AVE switch in the AVE position.
 - (4) ANTENNA channel-selector switch in the TOTAL position.
 - (5) TIME CONSTANT switch in the 3 SEC position.
- (d) Zeroing the op-amps on the preamplifier board. (See figures 19 and 20).
 - (1) Connect an external high-impedance dc voltmeter between test point number 1 (TP-1) on the pre-amp board and circuit ground. This permits measurement of the X-channel pre-amp input.
 - (2) Turn the power switch to the ON position.

NOTE: for accurate zeroing, the instrument should be turned ON for at least 15 minutes before adjustment of the zeroing potentiometers.

 - (3) Adjust the X-ZERO potentiometer on the pre-amp board for minimum indication on the voltmeter. The indication should be within ± 1 mV of zero (0 ± 1 mV).

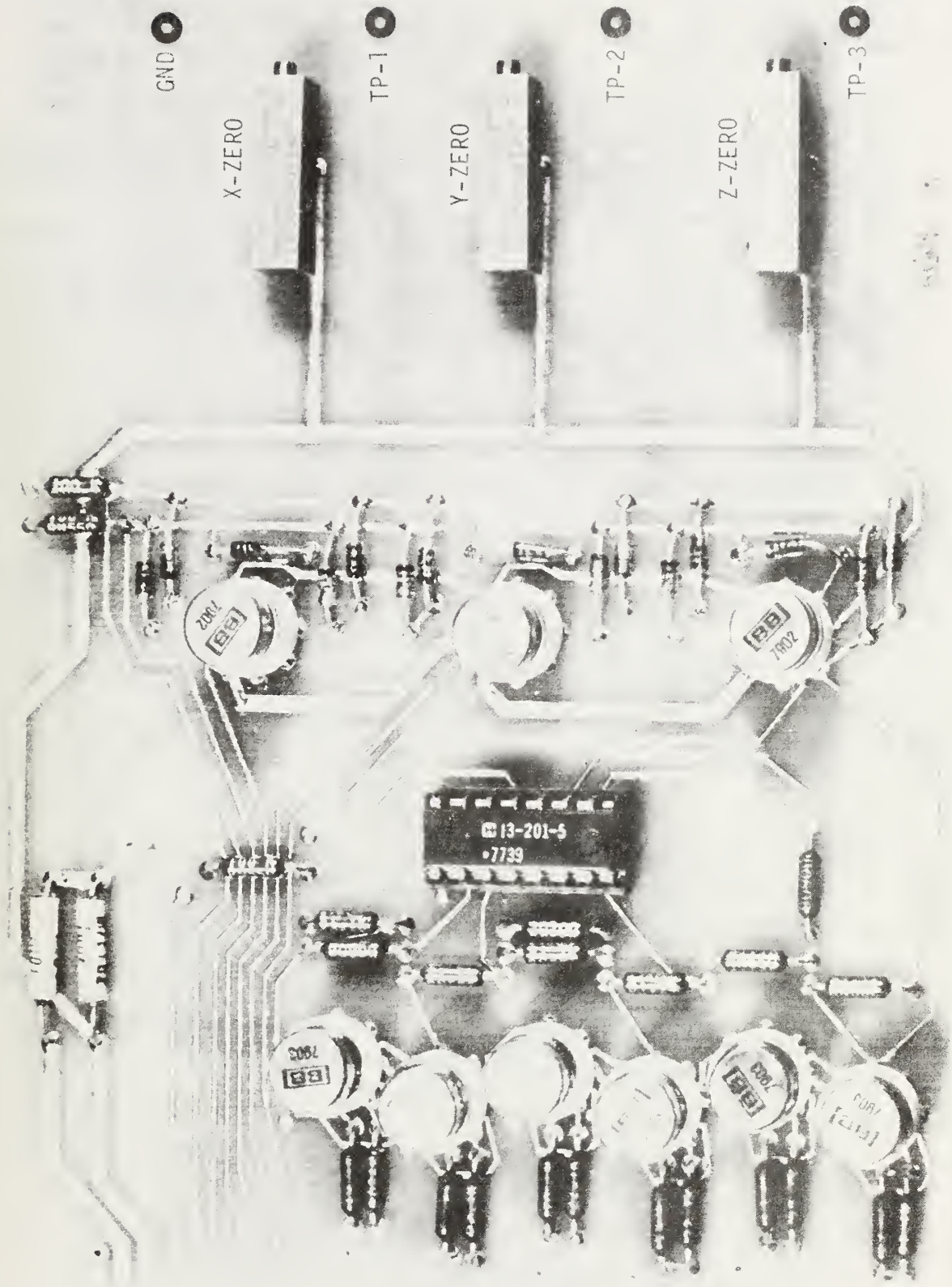


Figure 19. Photograph of the preamplifier board showing the zeroing controls and test points.

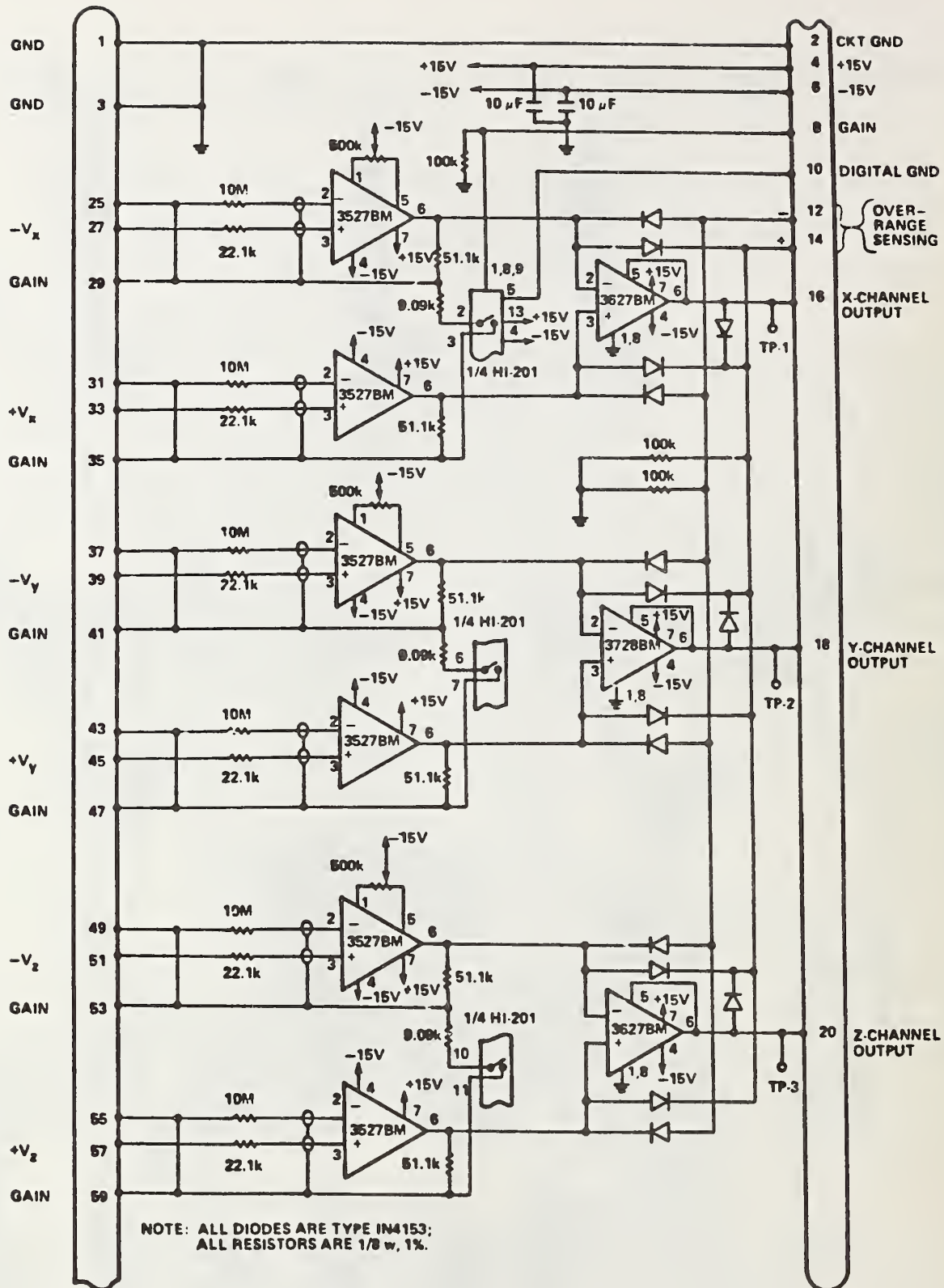


Figure 20. Schematic diagram of the preamplifier board

- (4) Connect the external voltmeter to TP-2 for measurement of the Y-channel pre-amp output.
 - (5) Adjust the Y-ZERO potentiometer to obtain a voltmeter indication of 0 ± 1 mV.
 - (6) Connect the voltmeter to TP-3 for measurement of the Z-channel pre-amp output, and adjust the Z-ZERO potentiometer to obtain 0 ± 1 mV.
- (e) Zeroing the op-amps on the shaping board. (See figures 21 and 22).
- (1) If this metering unit has not been aligned previously, insert an extender board between the shaping board and back plane of the metering unit. Set all six varistor potentiometers to approximately their center positions. These are the 100 k Ω potentiometers (R1 through R6) shown near the center of each figure.
 - (2) Connect the voltmeter to TP-4 (X-channel mid-amp output).
 - (3) Adjust the X-ZERO potentiometer to obtain a voltmeter indication of 0 ± 1 mV.
 - (4) Connect the voltmeter to TP-5 (Y-channel output) and adjust the Y-ZERO potentiometer for 0 ± 1 mV.
- (5) Connect the voltmeter to TP-6 (Z-channel output) and adjust the Z-ZERO potentiometer for 0 ± 1 mV.
- (6) Turn the front panel ANTENNA switch to the TOTAL position.
 - (7) Connect the voltmeter to TP-7 (adder output). Adjust the front panel ZERO control with a screwdriver for 0 ± 1 mV on the voltmeter.
- (f) Alignment of the shaping board. (See figures 21 and 22).
- (1) Turn the ANTENNA switch to the X position.
 - (2) Connect the voltmeter to TP-7 and adjust the front panel ZERO control for 0 ± 1 mV on the voltmeter.
 - (3) At a frequency of 10 MHz, set the field strength in the TEM cell to 0 dB A/m (range switch set at -20 dB A/m).
 - (4) Check to insure that the probe is positioned at the analytic angle and rotated axially for maximum response at a rotator angle of 0° .
 - (5) Connect the voltmeter to TP-4 and adjust the X-GAIN potentiometer for approximately -300 mV indication.

ADDER GAIN
 LO RANGE MID RANGE HI RANGE

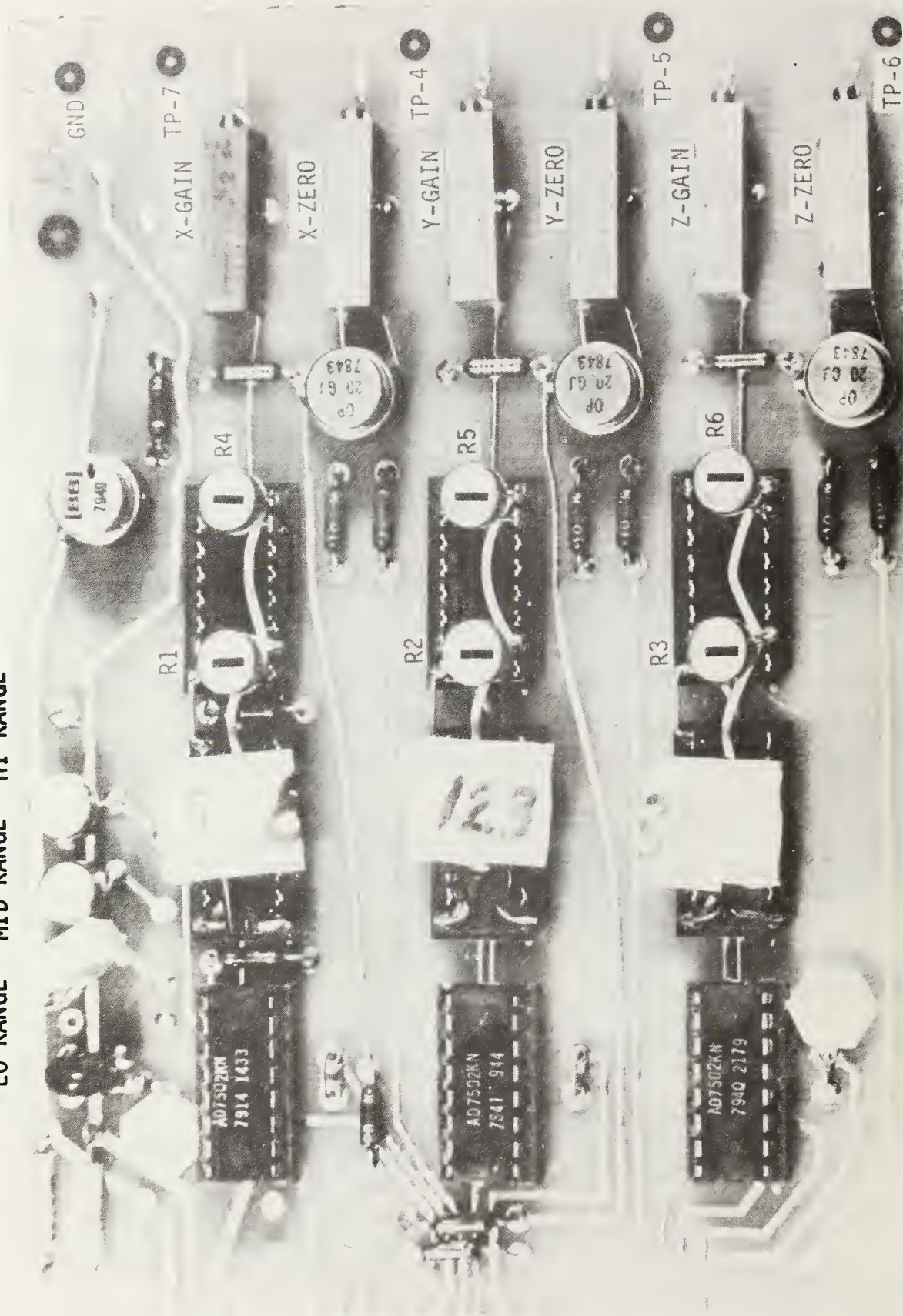


Figure 21. Photograph of the shaping board showing the zeroing and alignment controls and the test points.

- (6) Set the field strength to -10 dB A/m.
- (7) Connect the voltmeter to TP-7 and adjust the adder LO-RANGE gain potentiometer for 100 ± 5 mV.
- (8) Turn the RANGE switch to the 0 dB A/m step.
- (9) Set the field strength to 10 dB A/m.
- (10) Adjust the adder MID-RANGE gain potentiometer for 100 ± 5 mV.
- (11) Set the field strength to 20 dB A/m.
- (12) Adjust the R1 potentiometer for 1 volt ± 50 mV.
- (13) Repeat steps (6) through (12), if required, until the voltmeter readings are within the specified values.

NOTE: this completes the X-channel shaping and alignment for the lower two field-strength ranges.

- (14) Set the field strength to zero.
- (15) Turn the RANGE switch to the -20 dB A/m step.
- (16) Turn the ANTENNA switch to the Y position.
- (17) With the voltmeter connected to TP-7, adjust the front panel ZERO control for 0 ± 1 mV indication.
- (18) Turn the RANGE switch to the -20 dB A/m step.
- (19) Set the field strength to -10 dB A/m.
- (20) Rotate the probe axially to align the Y-axis dipole with the H-field to produce a maximum indication on the voltmeter.
- (21) Adjust the Y-gain potentiometer for 100 ± 5 mV.
- (22) Turn the RANGE switch to the 0 dB A/m step.
- (23) Set the field strength to 20 dB A/m.
- (24) Adjust the R2 potentiometer for 1 V ± 50 mV.
- (25) Repeat steps (18), (19), and (21) through (24) until the voltmeter readings are within the values specified above.

NOTE: This completes the Y-channel shaping and alignment for the lower two ranges.

- (26) Turn the ANTENNA switch to the Z position.
- (27) Repeat steps (14), (15), (17), and (19).
- (28) Rotate the probe axially to align the Z-axis dipole with the H-field to produce a maximum indication on the voltmeter.
- (29) Adjust the Z gain potentiometer for 100 ± 5 mV.
- (30) Repeat steps (22) and (23).
- (31) Adjust the R3 potentiometer for 1 V ± 50 mV.

- (32) Repeat steps (18), (19), and (29) through (31) until the voltmeter readings are within the limits specified above.

NOTE: This completes the shaping and alignment of all three channels for the lower two ranges.

(g) Adjustment of the logarithm board. (See figures 23 and 24).

- (1) With the power switch in the OFF position, insert an extender board between the logarithm board and the back plane of the metering unit.
- (2) Turn the RANGE switch to the -20 dB A/m step.
- (3) Connect the voltmeter between the output of the buffer amplifier (TP-8) and circuit ground on the logarithm board.
- (4) With the field strength set to zero, turn the power switch to the ON position.
- (5) With the PEAK/AVE switch in the AVE position, adjust the AVG-ZERO potentiometer for 0 ± 10 mV.
- (6) Connect the voltmeter to TP-9.
- (7) Set the field strength to read 100 mV on TP-8.
- (8) Adjust the LOG-ZERO potentiometer for 0 ± 1 mV.
- (9) Set the field strength to read 10 volts on TP-8.

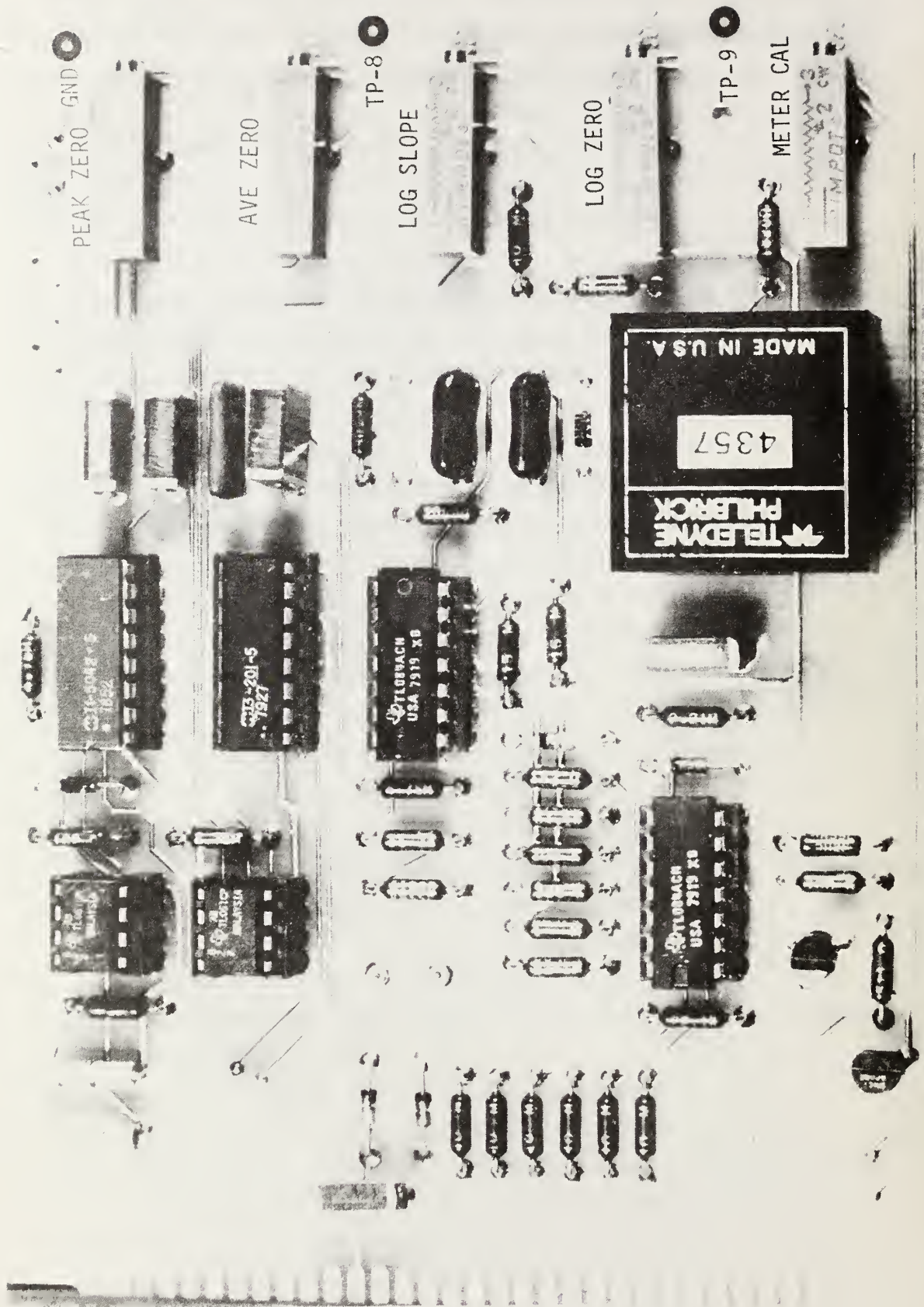


Figure 23. Photograph of the logarithm board showing the zeroing and alignment controls and the test points.

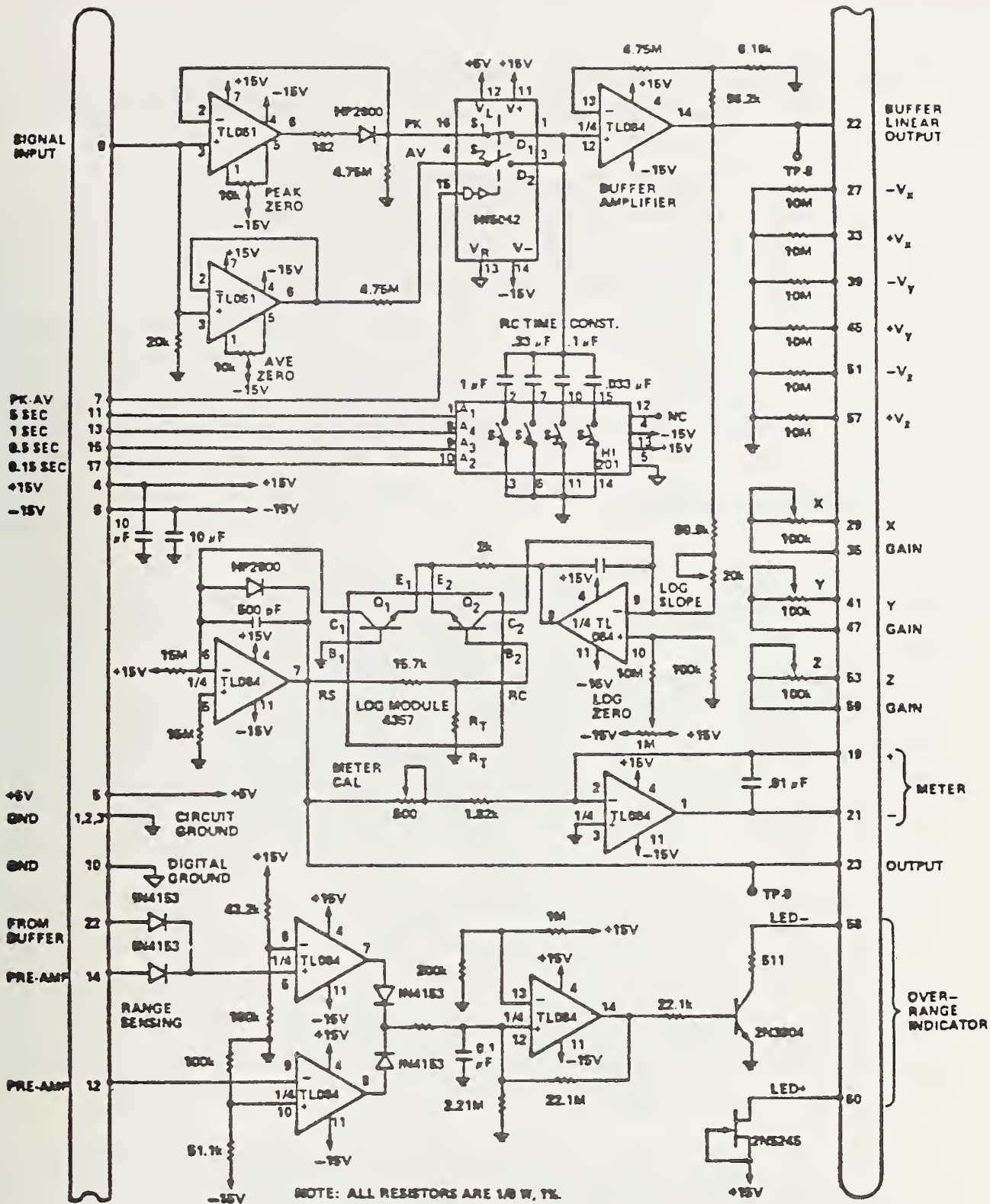


Figure 24. Schematic diagram of the logarithm board

- (10) Adjust the LOG-SLOPE potentiometer for $2V \pm 1 \text{ mV}$.
- (11) Repeat steps (7) to (10) until the voltmeter readings are within the above specified values.
- (12) Set the field strength to read 10 volts on TP-8.
- (13) Adjust the METER-CAL potentiometer for a 0 dB A/m indication on the front panel meter.
- (14) Set the field strength to zero.
- (15) Depress the PUSH TO ZERO button on the front panel and adjust the ZERO control for -20 dB A/m indication on the front panel meter.

NOTE: This completes alignment and adjustment of the MFM-10 meter.

7. Summary and Conclusions

This project was sponsored jointly by the National Institute of Safety and Health (NIOSH) and the National Bureau of Standards and is part of a continuing program to design electromagnetic radiation monitors for making accurate surveys of complex electromagnetic fields. The work at the National Bureau of Standards involves both theoretical and experimental work for quantifying electromagnetic fields and includes fabrication and calibration of prototype instruments. The immediate goal of this project was to develop an isotropic magnetic field monitor having a flat response from 300 kHz to 100 MHz. The measurement of the magnetic field meter (MFM-10) is from -20 to 24 dB A/m (0.1 to 16 A/m) with 1 A/m as the reference. The MFM-10 has a flat response within $\pm 1 \text{ dB}$ in its frequency range of 300 kHz to 100 MHz.

The relatively strong fields which are of primary interest generally occur close to a magnetic radiating source of high intensity and are likely to emit complicated field patterns. The only practical way to make quick surveys is with an isotropic probe such as the MFM-10 described in this work.

The meter measures the total magnetic-field magnitude, which is defined as the root-sum-square value of three perpendicular magnetic field components at the measurement point. This geometry permits easy and accurate measurements of either plane waves in the far zone or complex field structure in the

near zone. The meter can be used to measure the more intense leakage fields of industrial rf curing chambers and plastic sealing machines.

Other features of the MFM-10 are: a front panel switched to select measurement of either a single magnetic-field component or the root-sum-square value, and Schottky diodes as detector. The Schottky diode was chosen for its stability, high back resistance, high breakdown voltage, high sensitivity, and low temperature dependence.

The MFM-10 readout indication includes the overall effect of all magnetic-field components in the electromagnetic wave and all possible polarizations and arrival directions, for all frequencies within the passband of the meter. The meter indication is linearly proportional to the field magnitude expressed in dB referred to 1 A/m.

The MFM-10 is calibrated by immersing the probe in a standard field of known magnitude. The meter can be calibrated over the frequency range of 300 kHz to 100 MHz with an uncertainty of less than ± 1 dB. This calibration is performed as a function of frequency, amplitude, polarization, and orientation angle of the probe with respect to the magnetic field. This prototype meter has been supplied to NIOSH for their work in measuring possible hazards caused by industrial rf heaters and plastic sealers. Additional development work should be done to extend the frequency range of the probes.

This probe is a magnetic field version of the electric field probe previously developed [6] at the National Bureau of Standards. Much of the instrumentation and electronic principles of the EFM-5 (electric field monitor) have been incorporated in the MFM-10 with modifications done where it was necessary and applicable. The calibration, alignment, and adjustment procedures of [6] were modified for use in this MFM-10 report.

Research is now in progress at NBS to develop other monitors which will detect not only the magnetic field but both the magnetic field and electric field simultaneously with one antenna [7] so a complete characterization of the electromagnetic fields can be done. Possible approaches and preliminary evaluations have been made for future development of measuring the time phase angle between the electric and magnetic field.

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4. TITLE AND SUBTITLE Design of the National Bureau of Standards Isotropic Magnetic Field Meter (MFM-10) 300 kHz to 100 MHz			
5. AUTHOR(S) J. E. Cruz, L. D. Driver, M. Kanda			
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10. SUPPLEMENTARY NOTES ☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.			
11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) A broadband magnetic field meter has been developed at the National Bureau of Standards (NBS) for the frequency range of 300 kHz to 100 MHz. The isotropic antenna unit consists of three mutually orthogonal loops, each 10 cm in diameter. The magnetic field probe described in this paper has a measurement range of 0.1 to 30 A/m. The readout of the meter is in terms of the Hermitian or "total" magnitude of the magnetic field strength which is equal to the root-sum-square value of the three orthogonal magnetic field components at the measurement point. This magnetic field meter is nearly isotropic over its dynamic range. The electronic circuitry of the meter obtains the total magnitude of all field polarizations for all cw signals in the entire frequency band. The sensor is isotropic and is well suited for measuring the near field of an emitter, including regions of multiple reflections and standing waves. The meter can be used to monitor either the plane wave fields in the far zone of a transmitter, or the complicated fields very close to an rf leakage source. This report describes the design, performance and operating instructions for the MFM-10.			
12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons) electromagnetic field; electronic instrument design; field strength measurements; isotropic antenna; probe design.			
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